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AIR POLLUTION REGULATION 308



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APPENDIX H

November, 1987



Environment
Ontario

Hon. Jim Bradley
Minister

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APPENDIX H

AIR POLLUTION - GENERAL REGULATION MODELLING PROPOSALS

OCTOBER 1986



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Figure 1-2 illustrates the basic concepts of the model. The
regulation of the quality of the air is based on the
assumptions that the atmosphere is a mixture of air and
pollutants, and that the pollutants are distributed in the

AIR QUALITY MODELS SUITABLE FOR REGULATORY PURPOSES

1. The model is based on the following assumptions:
1.1. The atmosphere is a mixture of air and pollutants.
1.2. The pollutants are distributed in the atmosphere.

2. The model is based on the following assumptions:
2.1. The atmosphere is a mixture of air and pollutants.
2.2. The pollutants are distributed in the atmosphere.

3. The model is based on the following assumptions:
3.1. The atmosphere is a mixture of air and pollutants.
3.2. The pollutants are distributed in the atmosphere.

4. It is proposed that the model be used to estimate the
concentration of pollutants in the atmosphere. The model
is based on the following assumptions:
4.1. The atmosphere is a mixture of air and pollutants.
4.2. The pollutants are distributed in the atmosphere.

5. The model is based on the following assumptions:
5.1. The atmosphere is a mixture of air and pollutants.
5.2. The pollutants are distributed in the atmosphere.

6. The model is based on the following assumptions:
6.1. The atmosphere is a mixture of air and pollutants.
6.2. The pollutants are distributed in the atmosphere.

SUMMARY OF PRINCIPAL REVISIONS TO
"AIR QUALITY MODELS SUITABLE FOR REGULATORY APPLICATIONS"

1. Pages 1-4 Practical Aspects of Small Scale Modelling Applied to the Regulation of Air Quality has been rewritten to clarify the definitions used for Category A, B₁ and B₂ type sources.
2. Table 3, page 12 has been revised to express cloud cover, cc, in octants rather than percentage. The formula for the long-wave heat loss, H_L, has similarly been revised.
3. The previous proposal for plume penetration above the convective boundary layer has been removed.
4. The parameterization of the Brunt-Vaisala frequency squared (Eqn. (18)) has been re-written.
5. It is proposed that the formulation of terminal rise in a neutral boundary layer may be applied during stable conditions if the stability is sufficiently weak and the winds are sufficiently strong that the terminal neutral rise is less than the terminal stable rise.
6. The division between convective and neutral conditions based on surface heat flux, H₀, (pg. 15) has been revised from 50 Wm⁻² to 5 Wm⁻² based on recent observations reported by Shaw and Businger (1985) (J. Atmos. Science, 42 pp. 2563-2584).
7. The outline of the proposed method for determining critical meteorological conditions has been restructured to follow as closely as possible the description of proposed models.

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INTRODUCTION

This report describes several air quality models suitable for regulatory applications. These models have been abstracted from a review of the current scientific literature. In general, this review covered all types of short range models (e.g. Gaussian plume models, grid point models etc.) applicable for averaging times on the order of 30 minutes and greater. Models selected for inclusion in this overview are classified according to the meteorological conditions and the source situation. The models described are for continuous releases of non-reactive contaminants.

Prior to describing the models in the third section, some practical aspects of routinely applying small scale air quality models for source assessment are discussed in the next section of this report. In the final section some methods for determining the critical meteorological conditions which would result in the maximum concentration of a pollutant are outlined.

PRACTICAL ASPECTS OF SMALL SCALE MODELLING APPLIED TO THE REGULATION OF AIR QUALITY

The proposed system for maintaining air quality control by the regulation of current and future pollutant emissions requires that the air quality would be determined and compared with an established air quality standard or objective. To calculate the air quality using recent advances in small scale modelling, ideally one would estimate the contribution from each source (point, area or line) in the region to the air quality under all possible meteorological conditions. As well, it may be necessary to include the contributions from long-range transport and/or natural emissions to the overall air quality.

Frequently it is not necessary or practical to undertake a full set of model simulations to estimate the air quality. For simplification purposes it is possible to divide the sources being reviewed into two types:

Type A: Source complexes which yield small contributions to ambient air concentrations of a contaminant even under worst-case conditions. In this case small contributions from complexes are defined as those contaminant emissions from a complex which are equal to or less than 30 percent of the air quality standard set for the appropriate averaging time for each individual contaminant. Where source complexes consist of more than one source, the worst-case for the total plant can be computed by summing the worst-case for individual points of emissions.

Type B: Source complexes with contaminant emissions resulting in air concentrations which can be greater than 30 percent of the air quality standard set for the appropriate averaging time for each particular contaminant.

These may be divided into two groups:

- (1) Source complexes located in a region where a relatively uniform background concentration for the particular contaminant exists, regardless of origin.
- (2) Source complexes located in a region with several other large source complexes emitting the same contaminant in significant amounts.

Type A: Minor Source Complexes

A package of simple models has been prepared by the Atmospheric Model Development Unit to calculate the maximum concentration due to minor source complexes under worst-case meteorological conditions (also see the final section of this report). Worst-case meteorological

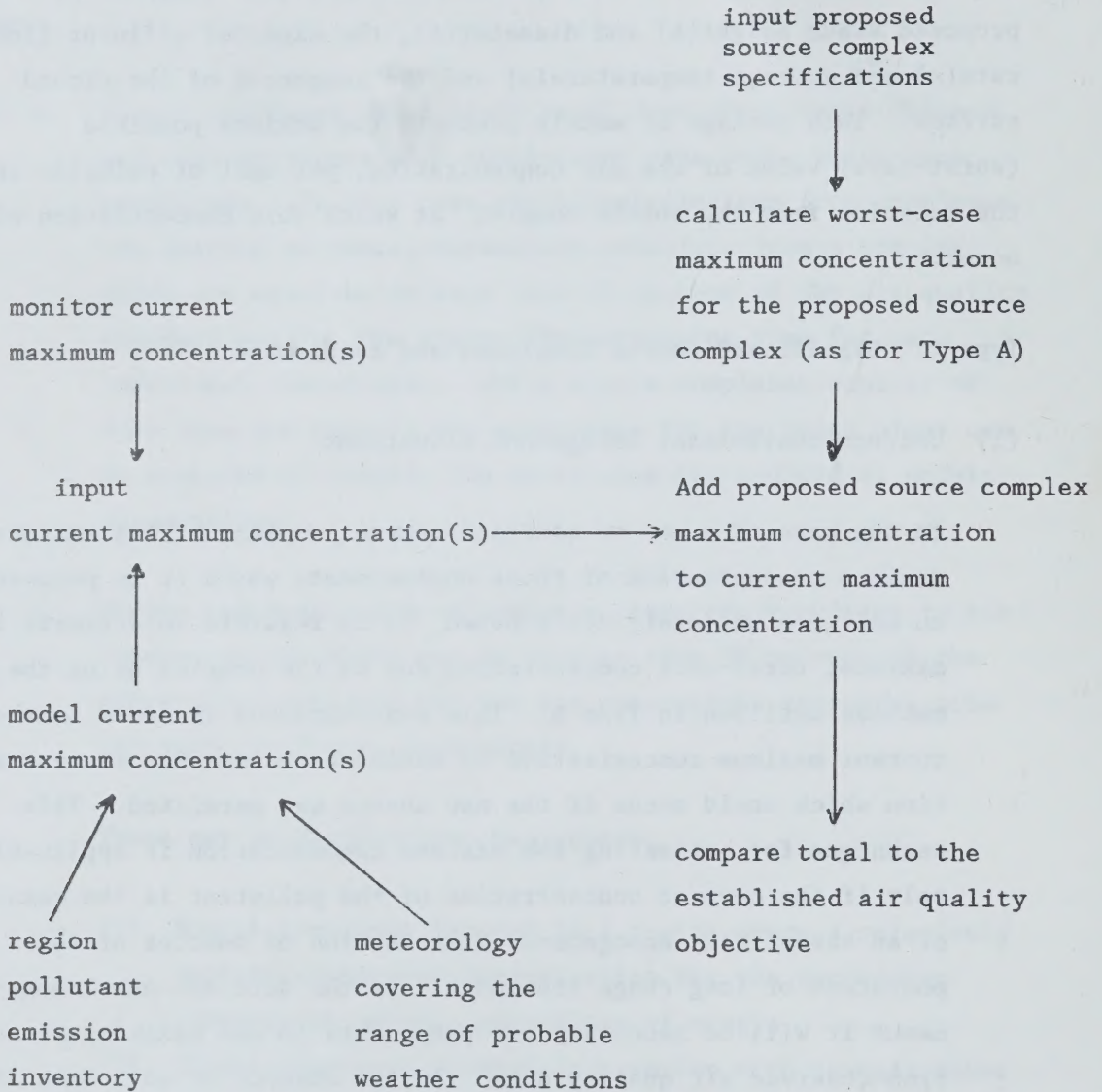
conditions are defined as the conditions which contribute to the highest ground-level concentration from the complex. The only inputs required are the specification of the source(s) (for example the proposed stack height(s) and diameter(s), the expected effluent flow rate(s) and average temperature(s) and the roughness of the ground surface. This package of models predicts the maximum possible (worst-case) value of the air concentration, per unit of emission and the location from the source complex at which this concentration will occur.

Type B: Significant Source Complexes and Background

(1) Uniform contaminant background situations

In the case of a new or modified source complex, if the current maximum concentration of those contaminants which it is proposed to emit are uniformly distributed, it is feasible to estimate the maximum, worst-case concentration due to the complex using the methods outlined in Type A. This concentration is added to the current maximum concentration to estimate the maximum concentration which would occur if the new source was permitted. This technique for estimating the maximum concentration is applicable only if the current concentration of the pollutant is the result of an essentially homogeneous distribution of sources of the pollutant or long-range transport. If the data are non-homogeneous it will be necessary for proponents to use maximum values from observed air quality data. In the absence of such data it will be necessary to model the current maximum concentration of the pollutant.

Schematically, the sources belonging to Type B(1) can be assessed in the following manner:

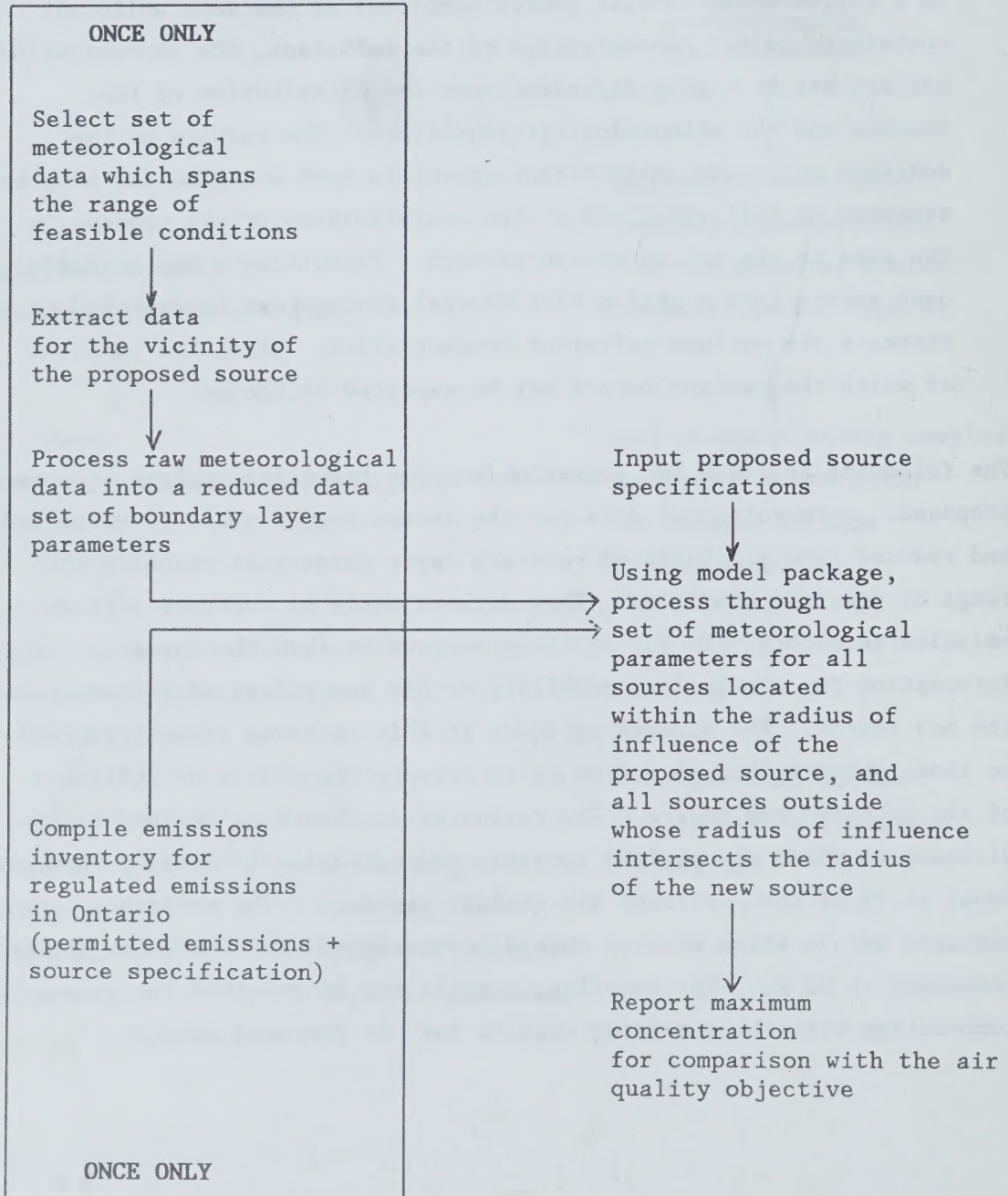


(2) Multiple Source Complex Situations - non-uniform contaminant background situation

In a region where several source complexes of the same pollutant contribute to the concentration of the pollutant, the concentration pattern may be highly dependent upon the distribution of the sources and the meteorological conditions. The results of the addition of another significant source to such a region can only be assessed by full modelling of the contributions of all sources in the area to the concentration pattern. Permitting a new significant source into a region with several sources can be expected to increase the maximum pollutant concentration. Also, the location at which the maximum occurs may be expected to change.

The following approach for assessing sources belonging to Type B(2) is proposed. Meteorological data for the source region would be extracted and reduced into a dataset of boundary layer parameters spanning the range of feasible conditions. This dataset would be combined with an emission inventory file for existing sources to form the input information for air quality modelling within the radius of influence of the new source. The sources included in this emission inventory would be those whose radius of influence intersects the radius of influence of the proposed new source. The radius of influence is defined as the distance to which the maximum possible concentration is greater than or equal to 5% of the pertinent air quality standard. The maximum distance out to which sources should be considered for inclusion in the inventory is 30 Km. The modelling results may be archived for combination with the modelling results for the proposed source.

A schematic chart of the manner in which sources belonging to Type B(2) could be assessed is shown in the following diagram:



SHORT RANGE AIR QUALITY MODELS

Outline of the Models

Several short range modelling techniques have been selected to satisfy the various meteorological conditions and site situations which are routinely encountered. These are summarized in Table 1.

Figure 1 shows a sketch of the evolution of the planetary boundary layer relative to the surface heat flux. Three general boundary layer meteorological grouping are made based largely on the value of the surface heat flux. Periods when the surface heat flux is positive will be referred to as convective. During convective (unstable) conditions the air in the planetary boundary layer is well-mixed due, principally, to large eddies generated by surface heating from incoming sunlight. Stable conditions refer to periods when the surface heat flux is negative (i.e. from the air to the ground). During these times mixing in the planetary boundary layer is very small and the ambient atmospheric conditions act to dampen any fluctuations in the flow (turbulence). Stable conditions occur at night or during winter when the ground is snow-covered. When the surface heat flux is zero the atmosphere is neither stable nor convective. These periods are treated as neutral. Within this report neutral stability refers to periods when the atmospheric conditions neither act to enhance nor to suppress the generation of turbulence. Transition periods usually do not persist but may be associated with events such as sunrise and sunset. During transition the boundary layer flow is not steady and can change continuously. In this report, the boundary layer during transition periods will be assumed for modelling purposes to be steady and to change only in a stepwise manner.

Very windy periods are considered separately. When the wind speed exceeds approximately six meters per second the turbulence generated by mechanical shear forces may dominate the turbulent state of the atmosphere. In this report, windy periods will be considered to be neutral.

Table 1
Short Range Modelling Methods for Average Air Concentrations
from Continuously Emitting Sources

Meteorological Conditions	Simple Situations			Special Situations		
	Near Surface	Elevated	Very Tall Stacks	Lakeshore Setting	Complex Terrain	Building Wakes
Convective	Surface	Convective Scaling	Convective Scaling	Fumigation model	Case by Case Consideration	Wake re-circulation to ground and enhanced dispersion based on building dimensions
Neutral	Similarity	Revised	Gaussian			
Stable	Modelling					

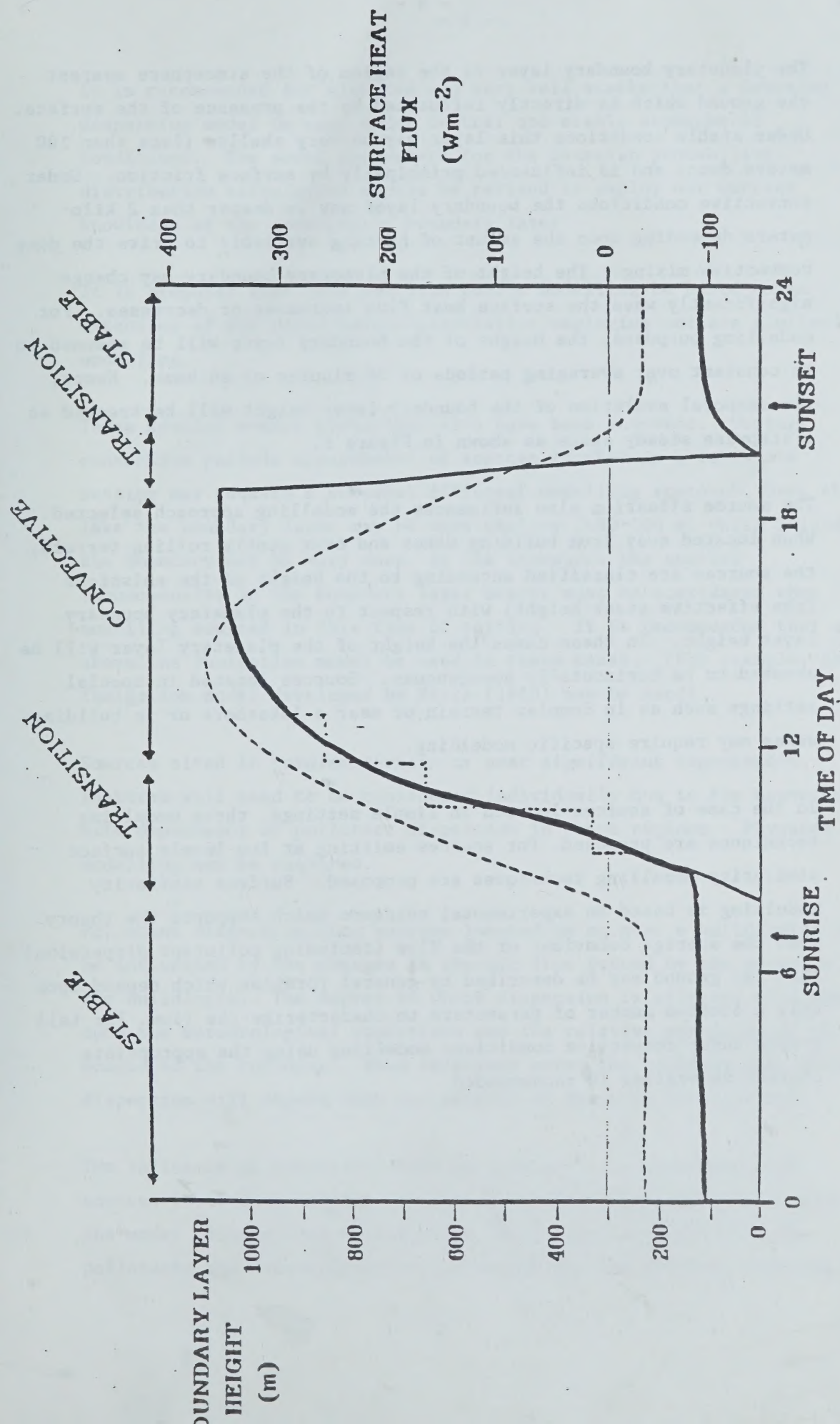


Figure 1: Schematic diagram of the evolution of the planetary boundary layer and of the surface heat flux sketched as functions of the time of day. The left axis shows the scale of the boundary layer height, z_1 . The right axis presents the scale of the surface heat flux, H_0 . The dark solid line denotes the height of the boundary layer. The dotted line shows a stepwise steady state approximation to the boundary layer height applied during transition periods. The surface heatflux is plotted using a dashed line.

The planetary boundary layer is the region of the atmosphere nearest the ground which is directly influenced by the presence of the surface. Under stable conditions this layer may be very shallow (less than 100 meters deep) and is influenced principally by surface friction. Under convective conditions the boundary layer may be deeper than 2 kilometers depending upon the amount of heating available to drive the deep convective mixing. The height of the planetary boundary may change significantly when the surface heat flux increases or decreases. For modelling purposes, the height of the boundary layer will be assumed to be constant over averaging periods of 30 minutes or an hour. Hence, the temporal evolution of the boundary layer height will be treated as a stepwise steady state as shown in Figure 1.

The source situation also influences the modelling approach selected. When located away from building wakes and over gently rolling terrain, the sources are classified according to the height of the emissions (the effective stack height) with respect to the planetary boundary layer height. In these cases the height of the planetary layer will be assumed to be horizontally homogeneous. Sources located in special settings such as in complex terrain or near a lakeshore or in building wakes may require specific modelling.

In the case of sources located in simple settings, three modelling techniques are proposed. For sources emitting at low levels surface similarity modelling techniques are proposed. Surface similarity modelling is based on experimental evidence which supports the theory that the average behaviour of the flow (including pollutant dispersion) near the ground may be described by general formulae which depend upon only a limited number of parameters to characterize the flow. For tall stacks under convective conditions modelling using the appropriate convective scaling is recommended.

It is recommended for elevated and very tall stacks that a Gaussian dispersion model be used under neutral and stable atmospheric conditions. The model parameters for the Gaussian probability distribution calculation should be revised to employ our current knowledge of the atmospheric boundary layer.

It is proposed that area and line source modelling be based on an extension of the point source calculation employing surface similarity modelling.

Three special source situations also have been reviewed. During convective periods assessments of sources located in a lakeshore setting may require a somewhat different modelling approach. Over the lake the boundary layer may be very shallow (~50-100 m) while inland the boundary may be very deep. At the lakeshore the spatial inhomogeneity in the boundary layer height must be considered when modelling sources in this type of setting. It is recommended that a shoreline fumigation model be used in these cases. (For example, the fumigation model developed by Misra (1980) may be used).

Sources sited in complex terrain or near significant topographic features will need to be considered individually due to the expected site dependency of pollutant dispersion in these regions. Physical modelling may be required.

Pollutant dispersion from sources located on or near a building(s) may be influenced by the changes in the air flow forced by the presence of the building(s). The degree to which dispersion is affected will depend upon the meteorological conditions and the relative proximity of the source to the building. When emissions enter the building wake their dispersion will depend upon the details of the wake flow pattern.

The influence of structure wakes on dispersion of emissions from sources located on or near the obstacles may be included empirically in the model calculations by enhancing the initial dispersion of the pollutants and reducing the source height for the effluent entering the

region of wake downwash. The details of dispersion from sources located on or nearby obstacles of various shapes can be very complex. Only extensive field tests or wind tunnel experiments can provide a detailed assessment of a complex site.

The description of the proposed models for simple sites is presented in the following three sub-sections. First, the methods for calculating the necessary boundary layer parameters are outlined. Second, the calculations of plume rise and the estimation of the potential penetration of the plume above the boundary layer are described. It is assumed that the portion of the pollutant emitted into the region above the boundary layer does not contribute to the local air concentration of the contaminant in the boundary layer.

The third sub-section describes the methods used for calculating air concentrations of contaminants due to emissions of non-reactive gases. The modelling techniques detailed are specifically for point sources. Line and area sources may be considered as aggregates of points over the area of the source.

Proposals for the Determination of the Necessary Boundary Layer Parameters

The routine application of air quality models requires that the information needed to perform the model calculations be readily available. First the required meteorological model input information will be described and then methods for determining the required boundary layer parameters are outlined.

(a) The Required Meteorological Information

The chart shown below summarizes the necessary meteorological data:

i) surface heat flux H_0

$H > 0$ $\circ$ Convective	$H \sim 0$ $\circ$ Neutral	$H < 0$ $\circ$ Stable
ii) boundary layer height z_i	ii) wind speed u	ii) wind speed u
iii) wind speed u	iii) surface roughness length z_o	iii) surface roughness length z_o
iv) temperature T_a	iv) temperature T_a	iv) temperature T_a
v) surface roughness length z_o		

The basic meteorological data used by the models are: u , the period (30 minutes or 1 hour) average wind speed at a height of approximately 10 meters (anemometer level); T_a , the period average ambient surface temperature; cc , the cloud cover as a fraction of the total sky; the ground snow cover; and, if available, the boundary layer height z_i . The surface roughness length, z_o , may be approximated as 1/30th of the height of the roughness elements such as buildings or trees. Table 2 lists z_o for various surfaces.

Table 2
Roughness Lengths for Various Surfaces

Surface	z_0 , cm
Very smooth (ice, mud flats)	0.001
Snow	0.005
Smooth sea	0.02
Lawn, grass up to 1 cm high	0.03
Lawn, grass up to 5 cm high	1-2
Lawn, grass up to 50 cm high	4-9
Fully grown root crops	14
Urban	100

After Pasquill (1974) and Seinfeld (1975)

Given the location (latitude and longitude) and the date and time period of interest, the surface heat flux H_0 may be calculated based on the assumption that it is proportional to the net solar radiation plus a small correction for the long wavelength loss of heat from the surface. Cloud cover reduces the net solar radiation reaching the surface and, also, decreases the long wave losses. The calculations follow the formulation report by Maul (1982):

$$H_0 = \alpha R + H_L, \quad (Wm^{-2}) \quad (1)$$

where R is the incoming solar radiation and depends on the time of day (t in decimal hours Greenwich Mean Time, GMT), the latitude of the source (L_R in radius), the longitude of the source (L_D in degrees), the day of year (d given as the Julian day, numbers 1 to 365 or 366) and the fractional cloud cover of the sky (cc in number of eighths).

$$R = 950 \beta (\cos(\phi) \cos(\tau) \cos(L_R) + \sin(\phi) \sin(L_R)), \quad (Wm^{-2})$$

where $\tau = \pi (t - t_n)/12$ and $t_n = 12 + L_D/15$ is the local noon time (GMT),

$$\phi = \text{ARCTAN} (0.4348 \sin(\pi(d-78)/180)).$$

β is the radiation reduction factor for the incoming solar radiation due to cloud cover. Table 3 lists β for given amounts of cloud cover (sky cover).

Table 3
Cloud Cover Reduction Factors for
Incoming Solar Radiation*

Sky Cover Percent	Octants (cc)	β
0.0	0	1.00
12.5	1	0.89
25.0	2	0.81
37.5	3	0.76
50.0	4	0.72
62.5	5	0.67
75.0	6	0.59
87.5	7	0.45
100.0	8	0.23

* After Maul (1982)

This calculation only applies between local sunrise and sunset, that is, for values of t between

$$t_{\text{rise}} = t_n - \frac{12}{\pi} \cos^{-1} (-\tan(\phi) \tan(L_R))$$

and
$$t_{\text{set}} = t_n + \frac{12}{\pi} (\cos^{-1} (\tan(\phi) \tan(L_R))).$$

The factor α is a function of the local surface ($\alpha = 0.35$ is assumed in the model) and it is an empirical proportionality factor between the incoming solar radiation and the surface heat flux. Note that when there is snow cover it is assumed that $\alpha = 0$. The above values are for typical rural lands.

$$H_L = -3. (8.5 - cc)$$

is the long wavelength heat loss at the surface.

Alternatively, H_o may be determined from measurements of net solar radiation or surface fluxes.

The convective boundary layer height, z_i , may be estimated using the nearest rawinsonde temperature versus height profiles when $H_o > 0$. Following the method of Holzworth (1967) z_i is calculated as the height above the ground at which the dry adiabatic extrapolation of the surface level temperature (T_a) intersects the 1200 GMT vertical temperature profile (700 EST).

When $H_o < 0$ the boundary layer height is calculated based on the wind speed and the Monin-Obukhov length scale. The neutral boundary layer height may be calculated based on the wind speed.

The surface (anemometer level) wind speed, u (ms^{-1}), the wind direction and the surface temperature, T_a ($^{\circ}\text{K}$), may be obtained from measurements taken near the source site at MOE, AES or other meteorological monitoring stations operated in an acceptable manner.

(b) Determining the Boundary Layer Parameters

The required boundary layer parameters are summarized below by meteorological category:

Convective	Neutral	Stable
i) Convective velocity scale w_*	i) friction velocity u_*	i) friction velocity u_*
ii) Monin Obukhov length scale L	ii) neutral boundary layer height H	ii) Monin Obukhov length L
iii) friction velocity u_*		iii) Stable Boundary Layer height H

It is assumed that when the surface heat flux is greater than 5 Wm^{-2} the boundary layer conditions are convective. The convective boundary layer parameters required in the continuous source models are:

the convective scaling velocity,

$$w_* = (g H_o z_i / (\rho c_p \bar{T}))^{1/3} ; \quad (2)$$

the Monin-Obukhov length scale,

$$L = -u_*^3 \bar{T} \rho_c / (g \kappa H_o), \quad (3)$$

$$\text{and } u_* = \kappa u / (\ln(z_a/z_o) - \Phi(z_a/L)) \quad (4)$$

the friction velocity, where

$$\Phi(z_a/L) = 2 \ln((1 + q)/2) + \ln((1 + q^2)/2) - 2 \text{ARCTAN}(q) + \pi/2$$

$$\text{and } q = (1 - 15z_a/L)^{1/4}.$$

$\bar{T}$ is the mean boundary layer temperature and is calculated from the near surface temperature T_a , the boundary layer depth z_i , and by assuming the temperature lapse rate is approximately adiabatic, hence,

$$\bar{T} = \frac{1}{2} (2T_a - 0.0098 z_i).$$

ρ is the density of air (approximately 1.2 kg/m^3), c_p is the specific heat of dry air at constant pressure ($c_p = 1005 \text{ J/kg/}^\circ\text{K}$) and g is the acceleration due to gravity (assumed to be 9.81 ms^{-2}). The von Karman constant, κ , is set to 0.35. z_a is the wind sampling height.

When the wind speed is greater than $6 w_*$ convective scaling is no longer appropriate for modelling (due to the increased importance of vertical wind shear). In these windy cases the boundary layer is assumed to be a neutral boundary layer. If the wind speed is less than $1.2 w_*$ the assumption that the concentration is independent of time (steady state assumption) is no longer valid. Modelling the concentration for these calm periods is not within the scope of currently available simple models.

The boundary layer is assumed to be stable if the surface heat flux is less than -5 Wm^{-2} . Under these conditions the boundary layer parameters required are:

the Monin Obukhov length scale, L , and the friction velocity,

$$u_* = \kappa u / (\ln(z_a/z_o) + 4.7 (z_a/L)). \quad (5)$$

When the Monin-Obukhov length scale, L , is plotted as a function of u_* based on measurements in a stable boundary layer it is observed (Venkatram, 1980b) that there is an empirical relationship between L and u_* . Venkatram (1980b) parameterized the Monin-Obukhov length as

$$L = 1100 u_*^2 \quad (6)$$

When the wind speed and hence u_* is small Venkatram's empirical fit is no longer valid (i.e., there are no real solutions to equations 5 and 6). Wind speeds which are less than the minimum necessary for real solutions are assumed to be calm. For modelling purposes, the wind speed during these calm periods is assigned the minimum value.

When the Monin-Obukhov length scale exceeds 500 meters it is proposed that for modelling purposes the boundary layer can be assumed to be a neutral boundary layer.

Stable boundary layer heights may be calculated using the other stable boundary layer parameters and Nieuwstadt's (1981) formulation.

$$H/L = 0.3 u_* (1 + 1.9 H/L) / (f_c L) \quad (7)$$

where f_c is the Coriolis parameter. (It is assumed that $f_c = 10^{-4} \text{ s}^{-1}$).

This equation reduces to the model of Brost and Wyngaard (1978) for L approaching zero and to the Tennekes (1973) neutral model for very large L . i.e.,

$$H = 0.3 u_* / f_c \quad (8)$$

The boundary layer is assumed to be a neutral boundary layer when there is negligible surface heat flux or when there are high winds. For modelling purposes it is proposed that the heat flux be assumed to be negligible if its value does not exceed 5 Wm^{-2} and is not less than -5 Wm^{-2} . The only boundary layer parameter required in this case is the friction velocity,

$$u_* = \kappa u / \ln(z_a/z_o).$$

Evaluating Plume Rise Parameters

When the efflux is less dense than the air into which it is released it will rise due to its inherent buoyancy. To calculate buoyant plume rise under stable and neutral conditions for continuous source modelling the plume rise formulations of Briggs (1975) are employed. During convective periods a plume emitted into the boundary layer will dilute rapidly and loop up and down as it is caught in the convective updrafts and downdrafts. The following chart summarizes the steps proposed for evaluating buoyant plume rise.

Convective	Neutral	Stable
i) determine non-dimensional buoyancy flux F^*	i) estimate plume rise, Δh	i) determine atmospheric stability parameter
ii) estimate plume rise, Δh for near surface sources	ii) estimate potential penetration of part of plume above H	ii) estimate plume rise, Δh
iii) calculate mass loss above z_i	iii) calculate mass loss above H	iii) estimate potential penetration above H of plume
	iv) estimate effective source height for material below H	iv) calculate mass loss above H
		v) calculate effective source height for material below H
		vi) estimate initial buoyancy generated spread of the plume

(a) Convective Conditions

During convective periods when the plume is released into the mixed layer of the boundary layer the downwind looping of the plume can result in the highest ground level concentrations. Venkatram (1980a) has expanded upon Briggs' (1975) plume "touchdown equation" to model the influence of convective downdrafts on a buoyant plume. This formulation circumvents the need to calculate plume rise in a convective boundary layer. In this calculation the required source parameters are:

- z_s , the stack height in meters above grade;
- r_s , the stack interior radius in meters at z_s ;
- T_s , the efflux temperature ($^{\circ}\text{K}$);
- w_s , the efflux exit velocity (ms^{-1}).

The initial buoyancy flux

The initial buoyancy flux

$$F = g \left(\frac{T_s - T_a}{T_s} \right) w_s r_s^2 \quad (10)$$

is calculated assuming the mean molecular weight of the plume is not significantly different from the mean molecular weight of air.

If a plume is released near the top of the neutral boundary layer and if it has sufficient buoyancy the plume may, at least in part, penetrate the boundary layer capping inversion. Manins (1979) and Briggs (1975) both give criterion for penetration above the neutral boundary layer; however, recent studies of plumes in convective boundary layers (e.g. Willis and Deardoff (1983)) suggest that very buoyant plumes may rise to the transition zone at the top of the boundary layer and, then following a period of time are subsequently mixed to the ground. Currently available plume rise models do not consider this phenomenon.

At present for convective conditions it is proposed to use Manins (1979) as the most conservative of the available plume penetration models. Manins defines the fraction of pollutant left in the boundary layer as:

$$\begin{aligned} f &= 1 \text{ if } P < 0.08 \\ f &= 0 \text{ if } P > 0.33 \\ f &= 0.08 P^{-1} - P + 0.08 \\ \text{where } P &= F\theta / (g u \Delta\theta_i [Z_i - Z_s]^2) \\ \Delta\theta_i &= 10^\circ\text{C} \end{aligned}$$

When a source emits inside the surface layer (i.e., the source height is less than the absolute value of the Monin-Obukhov length) the plume rise may be estimated using Briggs (1984) formula for rise in strong convection

$$\Delta h = 3 z_i F^{*3/5} \quad (11)$$

$$\text{where } F^* = F / (w_*^2 u z_i) \quad (12)$$

is the nondimensional plume buoyancy.

Also, the rise due to the plume momentum may be approximated as

$$\Delta h_m = 1.5 [F_m / (u u_*^2)]^{1/2}, \quad (13)$$

following Briggs (1975), where

$$F_m = T_a (w_s r_s)^2 / T_s. \quad (14)$$

The effective source height

$$z_e = z_s + \Delta h \quad (15)$$

may be estimated using the maximum of either the buoyancy or momentum driven plume rise.

When the wind speed is relatively high, the plume may be drawn downward into the wake of the stack. Briggs (1973) suggests that the plume downwash below the stack may be estimated by

$$h_d = 4(w_s / u - 1.5)r_s \quad (16)$$

when the efflux velocity w_s is less than $1.5u$.

(b) Stable Conditions

Final plume rise in the stable boundary layer has been shown by Briggs (1975) to be given by

$$\Delta h = 2.6 (F/uS)^{1/3} \quad (17)$$

where S is the Brunt-Vaisala frequency squared and may be calculated using the approximation

$$S = U_*^2 (0.74 + 4.7 Z_m / L) / (\kappa^2 L Z_m) \quad (18)$$

S is evaluated at a height, z_m , equal to the source height unless Z_s exceeds $2L$. In these cases, it is proposed that $Z_m = 2L$ be used when estimating S. This formulation is derived from substituting the stable temperature gradient surface similarity profile

$$\frac{\partial \theta}{\partial z} = \frac{\theta_*}{\kappa z} (0.74 + 4.7 z/L)$$

and the definitions

$$\theta_* = -\overline{\theta w_o} / u_*$$

and
$$L = -\theta u_*^3 / (\kappa g \overline{\theta w_o})$$

into the equation

$$S = \frac{g}{\theta} \frac{\partial \theta}{\partial z}$$

Alternatively, S may be derived from on site measurements. The wind speed used in equation 17 should be a near stack level value if the information is available.

During periods of relatively weak stability and strong winds (large L), the plume rise formulation for neutral conditions described in the following subsection may be used to estimate buoyant rise.

The effective source height, $z_e = z_s + \Delta h$, may be calculated using the maximum of either the buoyancy driven plume rise Δh or the momentum driven plume rise Δh_m calculated using Eqn. (13). If applicable, the effective source height is reduced by the plume downwash (Eqn (16)).

To test if the plume penetrates above the top of the stable boundary layer, it is assumed that the plume is evenly distributed in the vertical and that the plume width is one times the plume rise (following Briggs' (1975) suggestion). Then the plume penetration criteria are:

no penetration if $\Delta h < (H - z_s) / 1.5$ and the plume fraction remaining in the boundary layer is $f = 1$

total penetration if $\Delta h > 2(H - z_s)$ and $f = 0$

partial penetration otherwise and

$f = (1 - P)$ where $P = (1.5 - (H - z_s) / \Delta h)$

If only part of the plume remains in the boundary layer the effective plume height is defined as

$$z_e = 0.5 (H + z_s) + 0.25 \Delta h. \quad (19)$$

In the stable or neutral boundary layers the initial dispersion of the plume due to its own turbulence may be significant relative to the ambient turbulence, hence, the plume may be assigned an initial dispersion proportional to its plume rise (i.e. $\sigma_0 = \Delta h/4$).

(c) Neutral Conditions

Theoretically, under neutral conditions the ambient vertical temperature gradient does not inhibit the rise of a buoyant plume.

Briggs (1975) proposed that terminal plume rise in a neutral boundary may be approximated as

$$\Delta h = 1.3 F(1 + z_s/\Delta h)^{2/3} / u_*^2. \quad (20a)$$

However, Briggs noted that observations of plume rise in neutral conditions follow the "2/3 law" for rise of buoyant plumes as a function of downwind distance x , i.e.

$$\Delta h = 1.6 F^{1/3} u_*^{-1} x^{2/3} \quad (20b)$$

and that terminal rise was not reported for many of the cases. In this report, it is proposed that the minimum value of plume rise calculated using equations (20a) and (20b) be used to define Δh . If Δh exceeds Δh_m calculated using eqn. (13) the effective release height is $z_e = z_s + \Delta h$. Otherwise Δh_m is used to determine the effective release height.

To test if the plume, at least in part, rises above the top of the neutral boundary layer it is assumed (as in the stable case) that the plume has a step-wise distribution in the vertical with a half width of

$\Delta h/2$. The fraction of the plume below H is calculated for the neutral boundary layer plume rise as

$$\begin{aligned} f &= 0 \text{ if } \Delta h > 2 (H - z_s), \\ f &= 1 \text{ if } \Delta h \leq (H - z_s)/1.5, \end{aligned} \quad (21)$$

and $f = (1-P)$ otherwise, where $P = (1.5-(H-z_s)/\Delta h)$.

Methods for Calculating Downwind Concentration

The proposed methods for calculating concentration downwind from sources located in simple settings are summarized in the following chart. These models may be applied to single sources or groups of sources. Calculated concentrations for the individual sources may be added together to determine the total concentration due to all sources in the group provided that the relative source locations are used when evaluating the individual concentrations.

Methods of Calculating Concentration

Convective Conditions		Stable Conditions or Neutral Conditions	
$z_e \leq L $ (near surface source)	$z_e > L $ (elevated source)	$z_e \leq L/50$ or $z_s = 0$ (near surface source)	$z_e > L/50$ or $z_s > 0$ (elevated source)
i) Calculate $\overline{C_y}$ using method of Nieuwstadt (1980) ii) Calculate σ_y (Nieuwstadt, 1980) iii) Evaluate concentration $C(x, y, z=0)$ iv) determine the vertical distribution of $C(x, y, z)$ if necessary	i) determine most probable impingment distance x_i (Venkatram, 1980a) ii) calculate dispersion parameters σ_y and σ_z iii) evaluate concentration $C(x, y, 0)$	i) Calculate the virtual source location x_0 if $z_e > 0$ ii) Calculate model parameters $\bar{z}$ and $\bar{u}$ iii) Determine the lateral dispersion parameter σ_y iv) Determine the concentration $C(x, y, z)$ (Van Ulden, 1979)	i) Calculate dispersion parameters σ_z and σ_y ii) Calculate concentration $C(x, y, z)$ (revised Gaussian plume)

(a) Convective Meteorological Conditions

Concentration downwind of sources emitting into a convective boundary layer may be calculated using Nieuwstadt's (1980) convective scaling model when the effective source height above grade is less than the absolute value of the Monin-Obukhov length scale, L. Otherwise, Venkatram's (1980a) convective scaling, touch-down model may be used to calculate the surface concentration downwind of the source.

Near surface release

Nieuwstadt (1980) demonstrated that the cross-wind integrated, ground level concentration,

$$\bar{C}_0^y = \int_{-\infty}^{\infty} C(x, y, z = 0) dy,$$

can be expressed as a function of the non-dimensional downwind, distance,

$$X = x w_* / u z_i, \quad (23)$$

such that

$$\bar{C}_0^y = 0.73Q / u \bar{z} \quad (24)$$

where

$$\bar{z} / z_i = 0.812 X^{1.5} \text{ provided } \bar{z} < z_i \quad (25)$$

$$\text{otherwise } \bar{z} = z_i.$$

$\bar{z}$ defines the mean height to which the emission disperses downwind, and Q is the emission rate.

The cross wind dispersion of the plume is parameterized in terms of a Gaussian distribution. The lateral dispersion parameter σ_y is formulated as

$$\sigma_y = 0.6 z_i X / (1 + 0.7 X)^{\frac{1}{2}} \quad (26)$$

following the recommendations of Deardorff and Willis (1976) and Weil (1983). Hence

$$C(x, y, z = 0) = \frac{\bar{C}_o^y \exp(-y^2 / 2\sigma_y^2)}{(2\pi)^{\frac{1}{2}} \sigma_y} \quad (27)$$

The concentration for heights above ground level ($z = 0$) may be estimated using Horst's (1979) vertical exponential profile. Thus

$$C(x, y, z) = C(x, y, z = 0) \exp(-(z/1.52\bar{z})^{1.5}). \quad (28)$$

The above formulation assumes that $z_e = 0$. Non-zero source heights may be included in the above calculation by estimating a virtual ground level source location, x_o , such that $\bar{z} = z_e$ when $\bar{z}$ is calculated at $x = x_o$. Then the evolution of $\bar{z}$ downwind from the source is calculated by evaluating equation (25) at $x + x_o$. The evaluation of σ_y is unchanged.

Elevated releases into boundary layer

The average ground level concentration due to emissions released into the mixed layer of the convective boundary layer may be calculated by solving

$$F^{1/3} x_i^{2/3} - w_d x_i = -z_s u \quad (29)$$

for x_i assuming that w_d , the mean downdraft velocity, is defined as $w_d = 0.5 w_*$. The most probable touchdown distance, x_i , is used to determine the downwind concentration distribution

$$\bar{C}^y(x, z = 0) = \frac{fQ (1 + \text{erf}(p/\sqrt{2}))}{2\sigma_z u} \quad (30)$$

where $p = \ln(x/x_i) / \ln(x_i/x_i')$

and x_i' is the value of x_i calculated assuming $w_d = 0.75 w_*$. f is the fraction of the plume remaining in the boundary layer. Q is the emission rate. A crosswind Gaussian distribution is assumed, hence,

$$C(x,y,z = 0) = \frac{\bar{C}^y(x,z = 0)}{(2\pi)^{\frac{1}{2}} \sigma_y} \exp(-y^2/2\sigma_y^2). \quad (31)$$

Venkatram (1980a) parameterized σ_y and σ_z in terms of the nondimensional downwind distance X (see equation (23)) and the nondimensional plume buoyancy eqn. (12)

$$\text{such that } \sigma_y = 0.45 z_i (1.57 F^{*2/3} X^{4/3} + X^2)^{\frac{1}{2}} \text{ if } X \leq 1 \quad (32)$$

$$\sigma_y = 0.45 z_i (1.57 F^{*2/3} X^{4/3} + X^{1.72})^{\frac{1}{2}} \text{ if } X > 1 \quad (33)$$

$$\sigma_z = z_i (1 - \exp(-X - F^{*1/3} X^{2/3})). \quad (34)$$

(b) Stable Meteorological Conditions

Downwind of sources emitting into a stable boundary layer the concentration may be calculated using van Ulden's (1979) surface similarity model if the effective release height is very near the surface. In this report "near surface" is defined as z_e less than one-fiftieth the Monin-Obukhov length scale (i.e., $z_e \leq L/50$). Concentrations downwind from sources for which z_e is greater than $L/50$ are calculated using a revised Gaussian plume formulation.

Near surface releases

Using surface similarity scaling van Ulden (1979) showed that the cross-wind integrated, ground level concentration can be approximated as

$$\bar{C}_0^y = 0.73Q / \bar{u}z, \quad (35)$$

where $\bar{z}$ is the mean height to which the plume has dispersed and $\bar{u}$ is the mean transport wind speed for the plume. The value of $\bar{z}$ is calculated by solving the following equation;

$$x = 0.74 \bar{z} ((\ln(0.6\bar{z}/z_0) + 4.9 \bar{z}/L)(1 + 4.9\bar{z}/L) + 1.2\bar{z}/L) / \kappa^2. \quad (36)$$

Then the mean transport wind speed is given by

$$\bar{u} = u_* (\ln(0.6\bar{z}/z_0) + 4.7 \bar{z}/L) / \kappa. \quad (37)$$

The crosswind dispersion of the plume is parameterized in terms of a Gaussian distribution.

$$C(x, y, z = 0) = \frac{\bar{C}_0^y \exp(-y^2/2\sigma_y^2)}{(2\pi)^{\frac{1}{2}} \sigma_y}$$

The lateral dispersion parameter σ_y is calculated using the assumption that the initial plume spread σ_{y_0} and the ambient turbulence induced spreading σ_{y_a} are independent. Hence,

$$\sigma_y = (\sigma_{y_0}^2 + \sigma_{y_a}^2)^{\frac{1}{2}}$$

where

$$\sigma_{y_a} = \frac{1.3 u_*}{u} x (1 - z_e/H) f_y(x). \quad (38)$$

The form of the universe function $f_y(x)$ is taken from Pasquill (1976) and Irwin (1979)

$$\begin{aligned} f_y(x) &= (1 + (x/2500)^{\frac{1}{2}})^{-1}, \text{ if } x \text{ is less than 10 kilometers} \\ f_y(x) &= 33 x^{-\frac{1}{2}}, \text{ otherwise.} \end{aligned} \quad (39)$$

The vertical spread of the plume is assumed to follow an exponential form (Horst, 1979). Thus

$$C(x, y, z) = C(x, y, z = 0) \exp(-(z/1.52\bar{z})^{1.5}).$$

If the effective release height, z_e , is non-zero then the above calculations are modified in the same manner as in the convective near surface release model. Given the effective source height, equation (36) is solved for the virtual ground level source location, x_0 , assuming $z = z_e$. $\bar{u}$ is calculated using equation (37) for the height $\bar{z}(x + x_0)$.

Elevated releases into boundary layer

The downwind concentration due to an elevated release may be approximated using the Gaussian plume formulation. The lateral dispersion parameter, σ_y , may be calculated in the same manner as was employed in the stable, near surface release model. The vertical dispersion parameter, σ_z , may be estimated using the approximation of Wyngaard et al. (1975) for the standard deviation of the turbulent vertical velocity fluctuations

$$\sigma_w = 1.3 u_* (1 - z_e/H) \quad (40)$$

$$\text{then } \sigma_{z_a} = \frac{\sigma_w}{u} x f_z(x) \quad (41)$$

The form of the universal function $f_z(x)$ was selected, based on Irwin's (1983) review of various σ parameterizations to be

$$f_z(x) = (1 + 0.9 (x/50u)^{\frac{1}{2}})^{-1}. \quad (42)$$

This parameterization was proposed by Draxler (1976) in his initial investigation of the form of $f_z(x)$.

Including the initial plume spread σ_{z_0} gives

$$\sigma_z = (\sigma_{z_0}^2 + \sigma_{z_a}^2)^{\frac{1}{2}}$$

The downwind concentration due to an elevated release of gaseous emissions is determined by employing the above parameterizations of z_e , σ_z and σ_y in the Gaussian plume formulation

$$C(x,y,z) = \frac{fQ}{2\pi\sigma_y\sigma_z u} \left[\exp\left\{-\frac{(z-z_e)^2}{2\sigma_z^2}\right\} + \exp\left\{-\frac{(z+z_e)^2}{2\sigma_z^2}\right\} \right] \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\} \quad (43)$$

(c) Neutral Meteorological Conditions

The concentration downwind of sources emitting into a neutral boundary layer may be calculated using van Ulden's (1979) surface similarity model for sources with releases at the surface. Emissions with source heights greater than zero may be treated using a Gaussian plume model.

Near surface releases

Van Ulden's (1979) model for dispersion near the surface may be employed to calculate the concentration downwind from emissions with source heights, z_s , at the surface. The structure of this model has been described in the discussion of modelling near surface releases under stable conditions, however, the model parameters must be re-defined for the neutral boundary layer. Specifically, $\bar{z}$ is determined by solving

$$x = 0.73 \bar{z} \ln(0.6 \bar{z}/z_0)/\kappa^2 \quad (44)$$

$$\text{then } \bar{u} = u_* \ln(0.6 \bar{z}/z_0)/\kappa. \quad (45)$$

When z_e is non-zero, a virtual ground level source location is defined by solving equation (44) for x assuming $\bar{z} = z_e$. The mean transport wind speed $\bar{u}$ is calculated using $\bar{z}$ evaluated at $x + x_0$.

The lateral dispersion parameter σ_y may be evaluated using a formulation based on curves presented by Wyngaard et al. (1974) to describe the standard deviation of the cross-wind turbulent velocity fluctuations. Hence

$$\sigma_{y_a} = 1.3 \frac{u_*}{\bar{u}} x / (1 + (x/2500)^{\frac{1}{2}}), \quad (46a)$$

if x is less than 10 kilometers, and

$$\sigma_{y_a} = 1.3 \frac{u_*}{\bar{u}} x / (x^{\frac{1}{2}}/33), \text{ otherwise.} \quad (46b)$$

including the initial plume speed σ_{y_0}

$$\sigma_y = (\sigma_{y_0}^2 + \sigma_{y_a}^2)^{\frac{1}{2}}$$

Elevated releases in the boundary layer

Concentration downwind from an elevated release into the neutral boundary layer may be approximated using the Gaussian plume formulation. These calculations are identical to those undertaken for an elevated release into a stable boundary layer except that the formulation of the lateral and vertical dispersion parameters, σ_{y_a} and σ_{z_a} may be estimated using Briggs' (1973) analytical equations

$$\sigma_{y_a} = 0.08 \times (1 + 0.0001 \times)^{-\frac{1}{2}} \quad (47a)$$

and
$$\sigma_{z_a} = 0.06 \times (1 + 1.5 \times 0.0015 \times)^{-\frac{1}{2}} \quad (47b)$$

including the initial plume spreads

$$\sigma_y = [\sigma_{y_0}^2 + \sigma_{y_a}^2]^{\frac{1}{2}}$$

and
$$\sigma_z = [\sigma_{z_0}^2 + \sigma_{z_a}^2]^{\frac{1}{2}}$$

AN OUTLINE OF METHODS FOR DETERMINING CRITICAL
METEOROLOGICAL CONDITIONS

The determination of the maximum air concentration due to emissions from an isolated source of contaminant may be simplified somewhat by selecting the set of meteorological conditions which will result in the highest concentrations. Such weather conditions for the purposes of this section are referred to as "worst-case" or critical meteorological conditions. In the case of special source situations it is not practical to define worst-case meteorology due to the individual features of each site which influence the dispersion of pollutants in these areas.

The determination of the critical, worst-case meteorological conditions for sources located over rolling terrain emitting in a region not influenced by building wakes has been approached by seeking the conditions which would result in the maximum concentrations for each meteorological category (ie. convective, stable or transition) and for each source type (i.e. near surface, elevated or very tall stack). The only information required to assess the "worst-case" concentration is the specification of the source parameters such as the stack height and exit gas temperature.

The following chart outlines a method proposed for the determination of the maximum concentration due to isolated sources per unit emission rate based on the models described in the previous section.

I. INPUT THE SOURCE PARAMETERS

- source stack height and diameter
- area source dimensions
- exit gas temperature and flow rate
- calculate the source buoyancy assuming ambient air temperature of 20°C
- distance to nearest critical receptor (or plant boundary)

I.I Calculate the initial plume buoyancy flux and momentum flux



II. ASSESS THE SOURCE DESCRIBED UNDER CONVECTIVE CONDITIONS



II.1. Search through reasonable values of the boundary layer height z_i , for which the source height does not exceed z_i .



II.2 Estimate the maximum and minimum physically reasonable values for the convective velocity scale w_* based on the current value of z_i



(Note: z_i/w_* defines the Lagrangian time scale in the mixed layer (Lilly, 1968) and, therefore, these scales cannot vary randomly.)



II.3 Search through the range of wind speeds $1.2w_*$ to $6.0w_*$



II.3.1 Calculate the Monin Obukhov length scale L and determine if the source is elevated ($z_e > [L]$)

yes proceed to

II.3.3

no near surface



II.3.2 At the nearest specified receptor using the current minimum value for w_* :



II.3.2.1 Calculate the effective source location (x_0) as if the source were a surface source

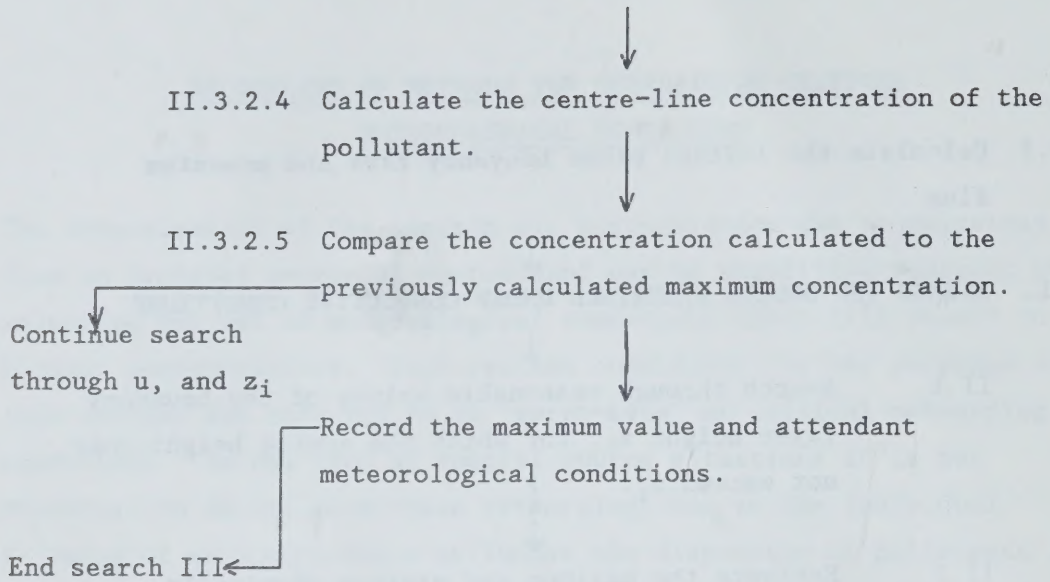


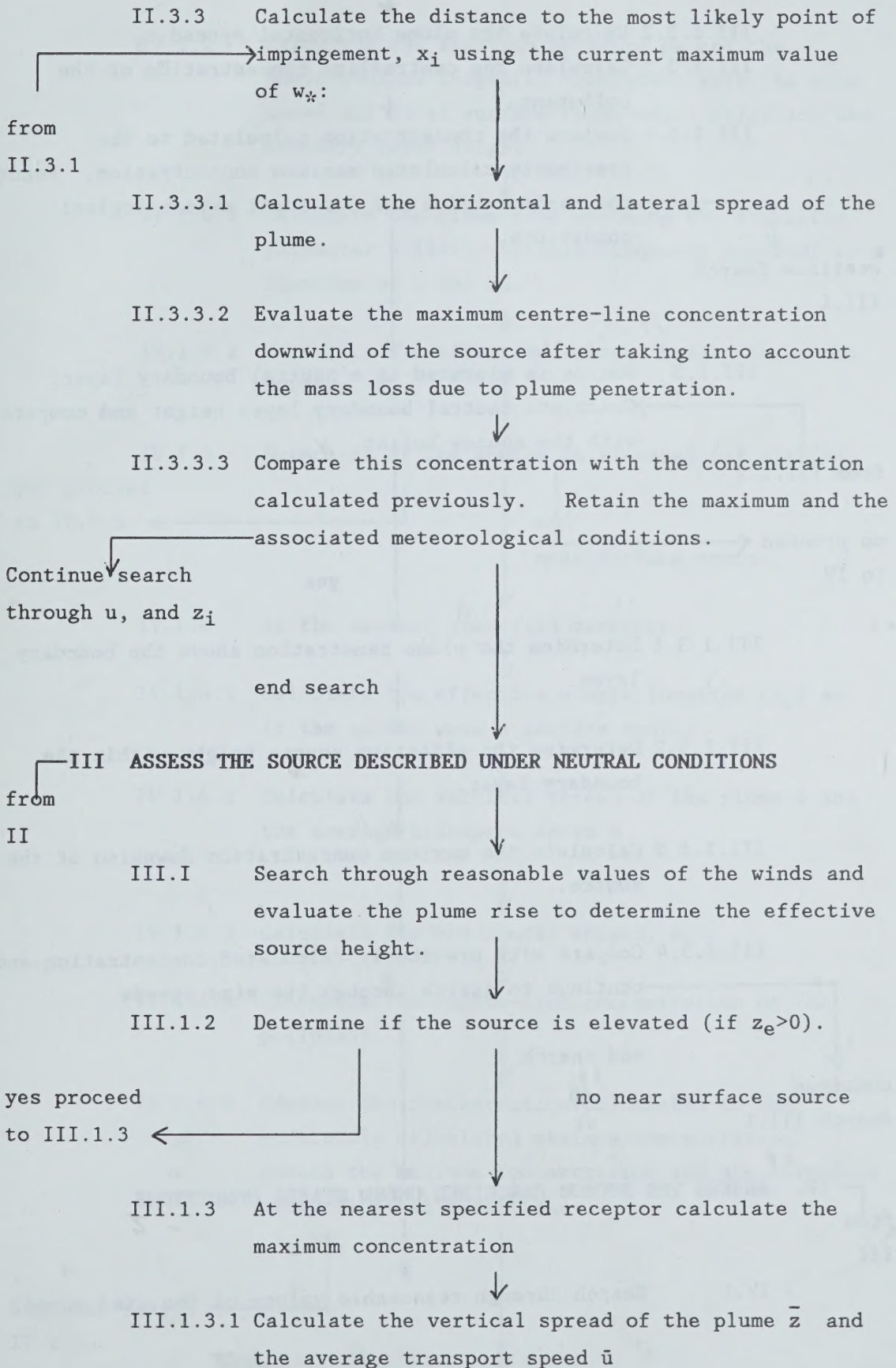
II.3.2.2 Calculate the vertical spread of the plume σ_z .

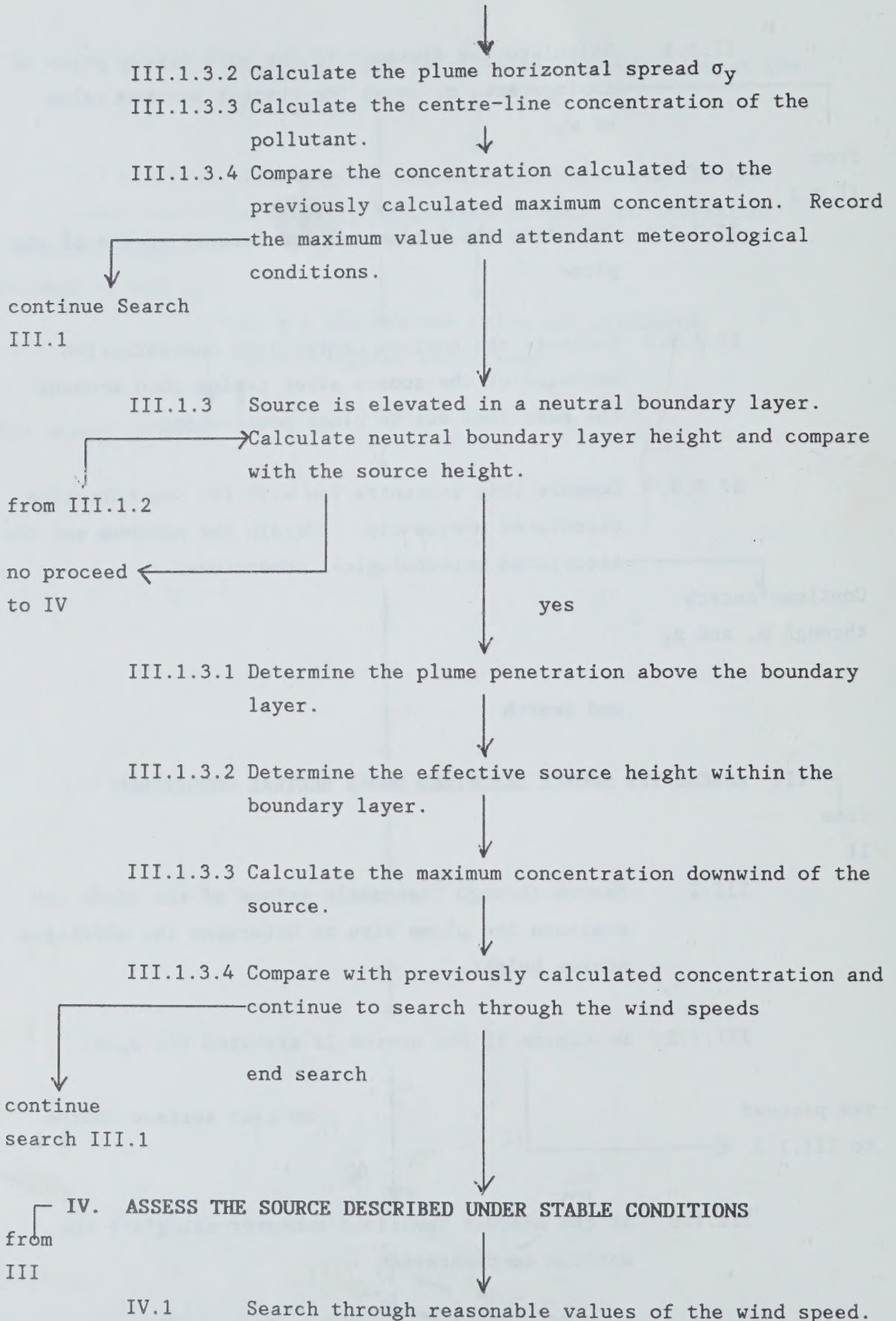


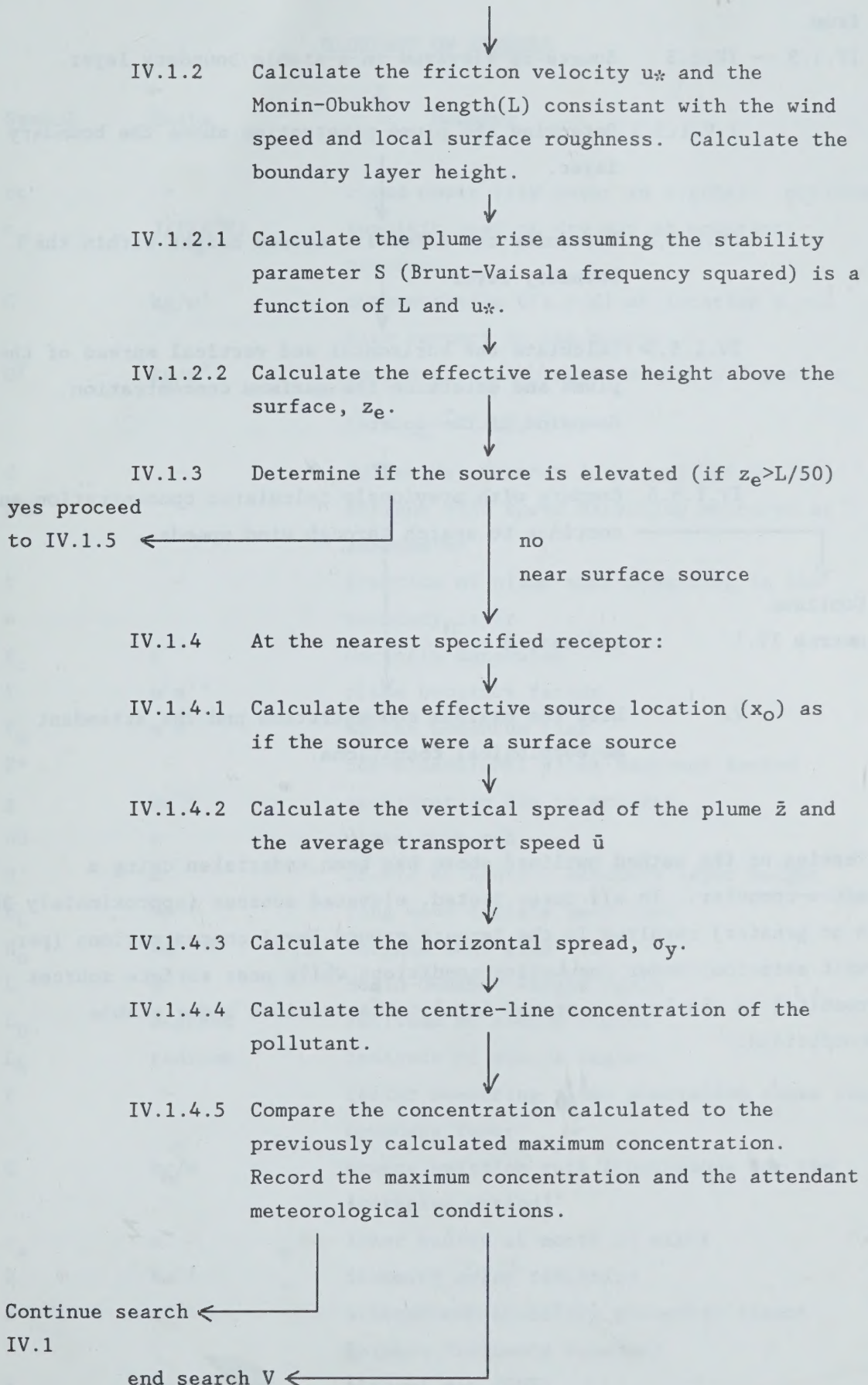
II.3.2.3 Calculate the plume horizontal spread, σ_y .











from

IV.1.3 — IV.1.5 Source is elevated in a stable boundary layer.



I.V.1.5.1 Determine the plume penetration above the boundary layer.



IV.1.5.2 Determine the effective source height within the boundary layer.



IV.1.5.3 Calculate the horizontal and vertical spread of the plume and determine the maximum concentration downwind of the source.



IV.1.5.4 Compare with previously calculated concentration and continue to search through wind speeds.



Continue
search IV.1

end search



V. List the maximum concentration and the attendant meteorological conditions.

Testing of the method outlined above has been undertaken using a micro-computer. In all cases tested, elevated sources (approximately 30 m or greater) resulted in the largest ground level concentrations (per unit emission) under convective conditions while near surface sources resulted in the largest ground level concentrations under stable conditions.

GLOSSARY OF SYMBOLS

Symbol	Units	Meaning
cc	-	cloud cover (sky cover in eighths): octants
c_p	J/(Kg°K)	specific heat of dry air at constant pressure
C	kg/m ³	concentration C(x,y,z) at location x,y,z with respect to the source
C ^y	kg/m ³	concentration integrated over y direction (i.e., $\int_{-\infty}^{\infty} C(x,y,z) dy$)
d	-	Julian day (number 1 through 365 or 366)
DIR	-	surface wind speed direction measured at anemometer
f	-	fraction of plume mass remaining in the boundary layer
f_c	s ⁻¹	Coriolis parameter
F	m ⁴ s ⁻³	plume buoyancy factor
F _m	m ⁴ s ⁻²	source momentum flux
F*	-	non-dimensional plume buoyancy factor
g	ms ⁻²	acceleration due to gravity
hd	m	plume downwash
H	m	stable or neutral boundary layer height
H _L	Wm ⁻²	long wave surface heat loss
H _O	Wm ⁻²	surface heat flux
L	m	Monin-Obukhov length scale
L _D	degrees	latitude of source region
L _R	radians	latitude of source region
P	-	factor measuring plume peneration above the boundary layer
Q	kg/s	source emission rate (continuous for the averaging period)
r _s	m	inner radius at mouth of stack
R	Wm ⁻²	incoming solar radiation
S	s ⁻²	atmospheric stability parameter (Brunt Vaisala frequency squared)
t	hr	time of day (GMT)
t _n	hr	local noon time (GMT for the source location)

Symbol	Units	Meaning
$\bar{T}$	$^{\circ}\text{K}$	mean boundary layer temperature
T_a	$^{\circ}\text{K}$	surface temperature
T_s	$^{\circ}\text{K}$	exit gas temperature
u	ms^{-1}	surface wind speed measured at anemometer level
$\bar{u}$	ms^{-1}	wind speed at average plume height
u_*	ms^{-1}	friction velocity
w	ms^{-1}	vertical velocity
w_d	ms^{-1}	most probable downdraft velocity
w_s	ms^{-1}	exit gas flow rate
w_*	ms^{-1}	convective scaling velocity
x	m	distance in the direction of the wind measured from the source
x_i	m	most probable downwind point of impingement of the plume
x_o	m	virtual source location for emissions from a near surface release (distance upwind from the source)
X	-	nondimensional distance downwind
X_i	-	most probable downwind point of impingement of the plume in nondimensional form
y	m	distance across wind
z	m	vertical distance from grade at x and y
z_a	m	anemometer level (approximately 10 meters)
z_e	m	effective source height (sum stack height and plume rise)
z_i	m	convective layer height
z_o	m	surface roughness length scale
z_s	m	stack height from grade
$\bar{z}$	m	average plume height
α	-	surface parameter relating incoming solar radiation to the surface heat flux ($\approx .35$)
β	-	cloud cover radiation reduction parameter

Symbol	Units	Meaning
$\frac{\partial \theta}{\partial z}$	$^{\circ}\text{Km}^{-1}$	partial derivative of potential temperature with respect to height
Δh_{capped}	m	plume rise in near neutral boundary layer capped by a temperature inversion plume rise
Δh	m	plume rise due to momentum
Δh_m	m	temperature change over the depth of the
ΔT	$^{\circ}\text{K}$	temperature inversion
Δz	m	thickness of capping temperature inversion
ϕ	radians	solar declination
π	-	mathematical constant $\pi = 3.14159$
κ	-	von Karmen constant ($\kappa = 0.35$)
ρ	kg/m^3	density of air near the surface
θ	$^{\circ}\text{K}$	potential temperature (a function of temperature and pressure)
θ_*	$^{\circ}\text{K}$	scaling temperature
$\overline{\theta w}_0$	$^{\circ}\text{Kms}^{-1}$	surface kinematic turbulent heat flux
τ	radians	solar elevation
σ_0	m	initial spread of plume due to buoyancy
σ_w	ms^{-1}	standard deviation of vertical velocities
σ_y	m	crosswind spread of plume (horizontal dispersion parameter)
σ_{y_a}	m	horizontal spread of plume excluding buoyancy generated spread
σ_z	m	vertical spread of plume (vertical dispersion parameter)
σ_{z_a}	m	vertical spread of plume excluding buoyancy generated spread

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REGULATION 308 REVIEW

MODELLING WORKSHOP

JUNE 25-26, 1986

SUMMARY REPORT

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1. INTRODUCTION

The Ontario Ministry of the Environment is proposing to revise the existing Regulation 308 models to properly include advances in science since the original models were formulated. The Ministry is also proposing to revise the regulation philosophy from the point of impingement calculations to source control and air quality criteria achievement.

The total proposed program was reviewed at a workshop during November, 1985. Several issues were raised at that workshop relating to the applicability of the proposed models. These were as follows:

1. How do the proposed model results compare with the existing models for some typical sources?
2. Have the proposed models been evaluated in an integrated manner?
3. What is the uncertainty in model outputs and how will this be taken into account in model applications?
4. How are these models going to be applied?

The Ministry held a second workshop on June 25 and 26, 1986 to address the above issues. The workshop was attended by people in Ontario familiar with the application of air quality models.

The workshop was divided into three sessions. All the presentations of results relating to the above issues were covered in the first session. The strengths and weaknesses of the models and their applications were discussed in the second and third sessions.

This report is a summary of the findings of this workshop.

2. EXPLANATION OF ISSUES:

Several sets of computer runs with the existing Regulation 308 and proposed models were carried out for different source configurations to show the comparison between the two modelling systems. The results are described later in this report. The key findings of this exercise are:

- a) The results for the worst-case calculations based on the proposed models are more realistic.
- b) The proposed models are applicable in all stability classes which are equally significant from the dispersion point of view. The existing models on the other hand are applicable for Pasquill-Gifford, C and D stability classes only.
- c) The proposed models have been evaluated with various data sets. This was the main criterion for the selection of the models.

In view of the many degrees of freedom which the atmospheric flows demonstrate, it is impossible to provide all the necessary inputs to models. Differences between model outputs and observations are inevitable. This is defined as uncertainty of model outputs.

There are two ways of including the model uncertainty in their application. The first method, which is a simple approach, is to use a safety factor. This is, however, arbitrary and does not guarantee elimination of exceedances.

The second method is a statistical approach. In other words, use the model uncertainty to determine the probability that the model simulated concentration for an event will remain within a certain multiplicative factor of the corresponding observed concentration. This information, along with the histogram of maximum concentrations within a time period can be used to determine the probable number of exceedances for the same period, which will occur if control is based on model simulations above.

The proposed models are designed to be used under three scenarios. In the first application only a single isolated source is considered. In this case a simple worst-case calculation suffices. This requires no major meteorological inputs.

In the second application, a point source is considered amongst a distribution of other small sources. In this case a simple worst-case calculation along with a background value suffices.

In the third application a large number of big sources are located close to each other. In this case detailed modelling is necessary. It also requires some meteorological data preprocessing to run the models.

3. AIR QUALITY MODELS SUITABLE FOR REGULATORY APPLICATIONS

An outline of the proposed models was presented at the June 25 and 26, 1986 Modelling Workshop with emphasis on the evaluation of these models with measurements and their applicability for regulatory use.

The proposed models were selected based on the following criteria:

1. that they be applicable to calculations of air quality over time scales of a $\frac{1}{2}$ hour or longer;
2. that they be scientifically credible;
3. that evaluation of the models with monitoring data shows good performance of the models in predicting downwind concentrations;
4. that application of the models is feasible for routine applications.

Recent understanding of the planetary boundary layer has resulted in significant changes (over the Pasquill-Gifford Gaussian type formulation) in the modelling of the diffusion of pollutants. An explanation of the meteorological factors affecting the diffusion of material released near the ground, or from elevated stacks in simple settings, is given in Chapter V of "Air Pollution General Regulation Workshop" November, 1985.

At the June 25 and 26 Modelling Workshop an overview of the evaluation studies undertaken for the proposed model was presented to demonstrate that the models are not only scientifically credible (i.e. they are based on recent knowledge of planetary boundary layer physics and have been peer-reviewed by the scientific community) but that they also show good performance in predicting downwind concentration. This presentation was accompanied by several figures showing the comparisons between observations and the model estimates. These figures are included on pages 68-108 of this appendix. The final column in Table 1 summarizes the monitoring data sets used to evaluate the models.

To evaluate models it is necessary to compare model performance against data collected from carefully executed diffusion experiments. These experiments are expensive and difficult. The number of field and laboratory experiments available for testing of models is limited. An important aspect of the evaluation data is the meteorological information collected during the experiments. It must include the important meteorological parameters.

The evaluation of the proposed mixed layer scaling model of Nieuwstadt (1980) for near surface releases was undertaken using the field data collected during the Prairie Grass Project (Barad, 1958). Although there have been several other field studies of near surface releases, only for the Prairie Grass Study was the mixed layer height measured. The model predictions of Nieuwstadt (1980) have been compared with 20 experiments conducted during the Prairie Grass Project. Nieuwstadt also compared his results with laboratory results collected by Deardorff and Willis (1975). Plots showing the comparison of model predictions with the experimental data are presented on pages 68 and

69. These two figures show that when mixed layer scaling is applied the observations are tightly clustered about model predictions indicating good performance of the model.

It is seen from these figures that the relationships between the scaled variables, which are established from theoretical considerations, are well supported by the data. A regression analysis for these figures is not meaningful since the same parameters appear in the scaled variables.

Predicted ground level concentrations calculated using Venkatram's (1980) convective scaling model for elevated releases has been compared with observations from three special field studies. Pages 70-72 show the results of this model evaluation. The first figure on each page presents the observed concentration versus the model prediction. In all cases the plotted results are tightly clustered about the one-to-one correlation line. The second figure on each page shows that, for the majority of measurements, the observations were within a factor of two of the model prediction.

To evaluate the proposed surface similarity model (van Ulden (1978)) for near surface releases under stable conditions it is necessary to have experimental data for the atmospheric stability parameter L . In general, the direct determination of this parameter using high quality turbulent flux measurement has not been done during dispersion field studies. Hence, indirect determination of L from other measurements is necessary. Nieuwstadt (1978) developed a method for calculating L and u_* from high quality measurements of profiles of wind speed and temperature and applied this technique to the Project Prairie Grass

Atmospheric Conditions and Relative Source Height	Modelling Technique	Primary Reference	Evaluation Study
near surface release, convective conditions	convective scaling (mixed layer similarity) modelling	F.T.M. Nieuwstadt, (1980) J. Appl. Meteor., 19, pp.157-162	- Prairie Grass field study - Lamb's numerical model - Deardorff and Willis physical model
near surface release, stable and neutral conditions	surface similarity modelling	A.P. van Ulden (1978) Atmos. Environ; 12, pp.2125-2129 (T.W. Horst (1979) J. Appl. Meteor)	- Praire Grass field study (van Ulden & Horst) - Green Glow field study - vertical distribution - σ_y - multiple datasets - Irwin, 1983
elevated release, convective conditions	convective scaling touch-down modelling	A. Venkatram (1980) Atmos. Environ., 14, pp.1-10	- Sudbury - Dickerson power plant - Morgantown
elevated release, stable conditions	Gaussian modelling with revised dispersion parameterization	J.S. Irwin (1983) J. of Clim. and Appl. Meteor., 22, pp.92-114 [Pasquill (1976), Draxler (1976)]	- σ_y multiple datasets - σ_z multiple datasets - σ_v Minnesota (Hanna, 1981)
elevated release, neutral conditions	Gaussian modelling with Briggs parameterization of dispersion	G.A. Briggs (1973) ATDL Report No. 79	- no specific model testing parameterized from fitting data
Plume Rise		G.A. Briggs, (1975) "Lectures on Air Pollution and Environmental Impact Analyses" AMS Boston Chapter 3	- multiple datasets

field study data. Availability of these boundary layer parameters facilitates evaluation of the surface similarity model with the Prairie Grass data for stable and near-neutral conditions.

The figure on page 73 shows the results of this intercomparison. The plot shows the scatter of normalized computed crosswind integrated concentration versus normalized measured crosswind integrated concentration. The clustering of data about the one-to-one line indicates good performance by the model. The parameterization of crosswind spread for low level releases was tested by Irwin (1983) using several field studies. His results are shown on page 74 and indicate that the model by Pasquill (1976) (recommended based on the Ministry's review of models) yields the best correspondence between over 600 measurements of lateral spread and the model predictions.

The study of Irwin (1983) also evaluated the dispersion parameters which are being proposed for the calculation of vertical and lateral spread under stable conditions from an elevated release. Figures showing Irwin's results are presented on pages 75 and 76. Irwin concluded that the formulation of Draxler (1976) yielded the best comparison with observations for vertical spread and the formulation of Pasquill (1976) performed well for lateral dispersion.

The above-described evaluation results of the proposed models show clearly their merit for application purposes. The Pasquill-Gifford type Gaussian formulations do not show such consistent performance against observed data.

It is proposed that the formulations of Briggs (1975) for plume rise in stable and neutral boundary layers be used for regulatory purposes. The figures on pages 77 and 78 show evaluation of the plume rise formulation for stable conditions for observations from large power

plant plumes, from small industrial chimneys and for balloon and wind tunnel data. The observed data initially follows the "two-thirds" law ($\Delta h \propto x^{2/3}$). Terminal rise in a stable atmosphere (as shown in each figure) is closely approximated by Briggs' formulation.

Evaluation of the model by Briggs for plume rise in a neutral boundary layer is shown on page 79. The upper figure on this page demonstrates that the initial observed plume rise during neutral conditions follows the "two-thirds" law. The lower figure compares observations of terminal rise in neutral conditions Briggs (1975). Although there are only limited data available for this evaluation the observations are clustered about Briggs' model prediction.

The observation of plume rise during convective conditions is extremely limited due to the rapid break-up of the plume. To estimate plume rise under convective conditions Briggs' (1975) formula is proposed for the limited application of estimating the effective release height (stack height plus plume rise) of the source for classification as either a near surface or an elevated release. The upper figure on page 80 compares Briggs' formula for terminal rise with a limited set of observations. Clearly, Briggs' formula will over-estimate buoyant plume rise for sources with large initial buoyancy; however, the proposed model for dispersion from elevated releases does not directly use Briggs' formula. Once a source is determined to be an elevated release it is proposed that Venkatram's (1980) convective, plume touch-down model be used to predict the concentration downwind from the stack.

The lower figure on page 80 presents a comparison of the touchdown formula proposed by Briggs and used by Venkatram, with laboratory data. The touchdown distance, x_T , calculated in the Venkatram model employs $w_d = 0.5w_*$. The very limited set of tank experiments suggest $w_d = (0.6 \pm 0.1) w_*$. The evaluation of Venkatram's model has already been demonstrated to show good correspondence between observed and predicted concentrations. This figure provides a secondary evaluation of the estimated touchdown (impingement) distance calculated in the model to approximate the compensating effects of plume buoyancy and convective downdrafts.

The fourth criterion used for model selection was that the models be feasible for routine applications. All models recommended are analytic in form and are therefore easy to implement in a computer program. They require only routinely available meteorological data or may be used with idealized, "worst-case" meteorological data. Once the model code and meteorological datasets are prepared, routine source evaluations may be undertaken by technical staff. The model package is structured in a modular form to permit easy implementation of future advances in our knowledge of planetary boundary layer science after legislative and other appropriate reviews.

4. DEVELOPMENT OF AN HOURLY METEOROLOGICAL DATA SET FOR APPLICATION OF THE PROPOSED MODELS

The objective was to compile a year-long hourly meteorological data set which covers the range of conditions encountered in the boundary layer. When doing this analysis it was not essential that any given hour correspond exactly with the turbulent state of the boundary layer which would be determined from a full set of boundary and micrometeorological measurements. It was only necessary that the ensemble of hourly cases represent the range and frequency of occurrence of the different boundary layer conditions. Therefore, the year-long hourly meteorology has been derived using only standard surface and upper air data available from the Canadian and U.S. weather services.

A basic thesis of the proposed modelling approach is that the boundary layer has three regimes in which it can exist. The turbulent characteristics of the three regimes referred to as stable, neutral and convective conditions are quite different.

Under convective conditions the ground is warmer than the air which creates an unstable layer of air above the ground. Thermal plumes are then initiated. The principal feature of a convective boundary layer is the organized, thermally driven vertical circulations which extend through the depth of the convective boundary layer. The figure on page 81 provides some observations of the strong updrafts ($1-2 \text{ m s}^{-1}$) and the induced downdrafts in a convective boundary layer.

Stable conditions occur when the ground is cooler than the air above, resulting in a negative heat flux. Mixing within the shallow stable boundary layer is normally very small, since in this case the atmospheric thermal structure acts to damp out vertical fluctuations in the flow pattern.

When the surface heat flux is small the atmosphere is classified as being neutral. Under neutral conditions the turbulent activity in the boundary layer is primarily mechanical turbulence generated from the wind field. For very windy conditions where mechanical turbulence dominates over thermal turbulence, the boundary layer is classified as neutral even if there is an upward heat flux.

The first objective in developing a meteorological data set was to provide a set of criteria for classifying the boundary layer as stable, neutral or convective using only routine surface meteorological observations. Once the basic stability class of the boundary layer has been established, the pertinent boundary layer properties needed for modelling dispersion in each situation are derived. The derivation of these parameters is described on p. 1-39).

Flint, Michigan, for 1983 was selected as the site for the year-long hourly meteorological record, because it had a continuous record of both surface and upper air data, was away from lakeshore effects and had a similar climatology to southern or central Ontario. The steps involved in processing the data are outlined on Table 2 (p. 54).

Page 82 gives an example of the use of the Holzworth method to derive the convective boundary layer height, Z_i , from a morning upper air temperature profile and hourly surface temperature through the day. The level at which a dry adiabatic (dashed lines) intersects the temperature profile is defined as the mixed layer height.

At the June 25-26 Modelling Workshop distribution graphs for some of the important meteorological fields were presented. These figures are shown on pages 83 through 95.

TABLE 2
DEVELOPMENT OF THE METEOROLOGICAL DATA SET

1. AFTER RETRIEVING THE SURFACE DATA FOR FLINT(1983), MISSING HOURLY VALUES FOR TEMPERATURE, WIND SPEED AND DIRECTION, AND CLOUD FRACTIONAL COVERAGE WERE INTERPOLATED USING DATA FROM THE SURROUND TIME PERIOD.
2. SNOW COVER WAS DERIVED FROM A COMBINATION OF OBSERVED PRECIPITATION AND TEMPERATURES ALONG WITH DAILY PUBLISHED SURFACE MAPS WHICH INCLUDE A SNOW LINE. (CLASSIFIED AS EITHER SNOW OR NO SNOW).
3. ALL OF THE DATA WERE EXAMINED VISUALLY FOR UNREASONABLE TEMPERATURE OR WIND SPEEDS. (ONLY 10-20 DATA POINTS WERE FLAGGED AND REPLACED).
4. DAYTIME CONVECTIVE MIXED LAYER HEIGHTS WERE DERIVED FROM THE MORNING UPPER AIR ASCENT AND HOURLY SURFACE TEMPERATURE THROUGH THE DAY. (HOLZWORTH)
5. A MINIMUM CONVECTIVE BOUNDARY LAYER HEIGHT OF 50 M WAS IMPOSED ON THE z_i VALUES DERIVED FROM THE HOLZWORTH METHOD.
6. SINCE THE PROPOSED AIR QUALITY MODELS CANNOT HANDLE CALM CASES, MINIMUM WIND SPEEDS WERE IMPOSED FOR EACH STABILITY CLASS

STABLE: 2.85 m s^{-1} (A FUNCTION OF SITE ROUGHNESS) (IN THIS CASE $z_o = 3 \text{ cm}$)
NEUTRAL: 1.5 m s^{-1}
CONVECTIVE: $1.2 w^* \text{ m s}^{-1}$
(1.5 m s^{-1} MINIMUM)

FLAGS WERE INTRODUCED INTO THE DATA SET TO KEEP TRACK OF ALL THINGS DONE TO THE DATA.

Page 83 presents a histogram of the frequency of stable, neutral and convective cases in the year-long data set. These are given as bar graphs summing to 100% for each hour of the day. For example, local noon (17 GMT) shows ~70% convective, >20% neutral and <10% stable hours. Included in the convective hours are periods for which no mixed layer height Z_i was available (i.e. air quality model runs can therefore not be performed).

This annual graph depicts diagrammatically that convective and stable cases provide about 60% of the total hours during the year. Pages 84 and 85 give a "summer" and "winter" season breakdown of the stability classification. As expected, summer days show more convective hours than do winter days. Also, because overcast conditions are less common during the summer, the summer nighttime stability is more stable than the winter's.

Page 86 shows the very broad distribution of convective boundary layer heights produced for the year's data. These range from the shallow boundary layers found in the early morning to very deep mid-afternoon values of Z_i . Page 87 shows average Z_i values as a function of the time of day.

Pages 88 and 89 depict frequency graphs for neutral and stable boundary layer heights respectively. The neutral histogram is quite broad while the stable distribution curve shows a large percentage of shallow boundary layers (<45 m) with a tail of heights extending past 300 m.

Page 90 presents the distribution of wind speeds which demonstrates a broad peak from 2 to 4 m s⁻¹. Thirty-year climate normal wind data for Flint have an average wind speed about 10% higher than the 1983 data, primarily because a larger percentage of higher wind cases (>9 m s⁻¹) occur in the climate normal data.

The wind speed distribution after imposing minimum wind speeds for stable, neutral and convective cases is presented on page 91. The large peak for the 3 m s^{-1} category occurs because of the 2.85 m s^{-1} minimum wind speed imposed for stable cases.

Page 92 presents a histogram for wind direction frequencies. As expected there is a larger percentage of winds from the south to west sectors.

A histogram depicting the annual frequency distribution of the surface friction velocity, u_* , is found on page 93.

The final figures presented during the Workshop show the distribution of stabilities in the boundary layer. Page 94 reveals that $\sim 40\%$ of the cases were neutral (i.e. $1/L \approx 0$) with about 25% convective ($1/L < 0$) and 35% stable ($1/L > 0$). Page 95 presents more detail of the distribution of non-zero values of $1/L$. The larger negative and positive values are the most unstable and stable cases respectively.

Overall these histograms indicate the range and the frequency of occurrence of the meteorological parameters in the year's data set. Seasonal and monthly plots of these parameters have been considered in addition to the annual distribution curves shown.

5. RESULTS OF THE APPLICATION OF THE PROPOSED MODELS

The application of the proposed modelling package for sources in simple settings was presented at the June 25-26 Modelling Workshop. Five generic sources were selected. The source parameters for the stacks considered are summarized in the table presented on page 96. For each of the sources the proposed model package was used to calculate the downwind maximum hourly average concentration for the annual meteorological dataset. Pages 97-101 present histograms of the hourly average maximum calculated concentration downwind from the sources. In each case only periods when the calculated concentration exceeds five non-specific concentration units are included in the histograms (note: each source's emissions have been scaled to yield maximum values between 100 and 250). Each bar on the horizontal (concentration) axis spans five concentration units.

5.1 Comparison with Regulation 308

Source 1: The figure on page 97 presents the histogram of modelling results for the maximum concentration downwind from source #1. For the generic municipal incinerator the largest hourly average concentration, $C_{\max}$, calculated using the annual meteorological dataset was 189 concentration units predicted for the convective meteorological conditions listed on page 97. The hourly calculated average ground level maximum concentration exceeded five non-specific concentration units during 5577 hours of the year (8760 hours). The remaining hours included 635 hours when the meteorological data necessary to calculate concentration were not available.

The calculated maximum ground level concentration determined using the model calculation prescribed in Regulation 308 is 170 concentration units. The proposed model calculations for hourly ground level maximum concentration exceeded the Regulation 308 value for six hours during the 8125 hours for which calculations were performed.

Source #2: The modelling results for source #2 are shown in the figure on page 98. The maximum hourly average concentration based on the year of meteorological data developed for Flint, MI, is 220 non-specific concentration units. The annual maximum concentration is determined to occur for the convective meteorological conditions summarized on page 98. The calculated concentration exceeded five concentration units for 4167 hours during the model year.

The Regulation 308 calculation for ground level maximum concentration is 121 concentration units. For this large generic municipal incinerator the hourly average ground level maximum concentration calculated using the proposed models exceeded the Regulation 308 maximum for 41 hours during the model year.

Source #3: Source #3 represents a generic sewage sludge incinerator. The figure on page 99 presents the modelling results for this source. The calculated annual maximum hourly average concentration was 200 units and was determined to occur for the convective meteorological conditions listed on the figure. Calculated maximum ground level, hourly average concentration exceeded five non-specific concentration units for 6166 hours during the model year.

The calculated maximum concentration for this source based on Regulation 308 is 105 concentration units. The hourly average calculated maximum ground level concentrations determined using the proposed model package exceeded the value calculated using Regulation 308 for 326 hours during the model year.

Source #4: This source has been included in the model calculations as it is similar to the tallest industrial source in Ontario. The proposed modelling package was used to calculate the hourly average maximum concentration in the first 25 kilometers downwind from this source. Based on these calculations, the concentration exceeded five non-specific concentration units for 1671 hours during the model year. These hours were all during convective periods and the annual maximum calculated concentration was 189 units for the convective conditions noted on the figure on page 100.

The calculated maximum ground level concentration based on Regulation 308 is 38 concentration units. The hourly average maximum ground level concentration based on the proposed models exceeded the Regulation 308 value during 1184 hours of the model year.

Source #5: Source #5 represents a large industrial chimney. The histogram shown on page 101 presents the modelling results for this source. For 2392 hours of the model year it was calculated that the hourly average ground level maximum concentration would exceed five concentration units. The annual maximum concentration was calculated to be 168 concentration units. The maximum was determined for the meteorological conditions listed on the figure on page 101.

The maximum concentration calculated using Regulation 308 was 80 concentration units. The proposed model calculations exceeded this value for 54 hours during modelling year.

As noted previously, Regulation 308 does not include modelling techniques which reflect our current understanding of the dispersion from releases into the convective boundary layer. The importance of convective conditions has been illustrated for each of the five sources considered. In all cases it was convective conditions that yielded calculated maximum concentrations greater than the maximum concentration calculated using Regulation 308. In addition, the previous discussion of the meteorological dataset showed that annually convective conditions occur approximately 25% of the time.

It should be noted that the sources considered for this illustration of the application of modelling package all represent elevated releases in the boundary layer. For near surface releases examination of the proposed models shows that the annual maximum ground level concentration would occur for stable atmospheric conditions and would be located at the closest specified receptor downwind of the source.

5.2 Worst-Case Model Calculations

To simplify the assessment of isolated sources in simple settings it has been suggested that the proposed package of models be applied for critical meteorological conditions to determine the worst-case concentration for the source under consideration. For stable and neutral meteorological conditions it may be demonstrated that the wind speed is the most important meteorological parameter. Hence, to

determine the worst-case meteorological conditions for stable and neutral conditions it is necessary to scan through the plausible range of wind speeds. To demonstrate the application of worst-case modelling the range of wind speeds (1.5 - 15 m/s) observed for the 1983 Flint, MI, dataset were used (see the histogram on page 90).

The determination of the critical meteorological parameters during convective periods requires the evaluation of the worst-case combination of mixed layer height Z_i and the convective velocity scale w_* . Page 102 presents a plot of Z_i versus w_* for data from several special studies (large symbols) and for the Flint, MI, dataset. It is clear from this figure that for any given value of Z_i it is possible to define an upper bound on the plausible values of w_* which may be associated with Z_i . Physically, this is reasonable as Z_i and w_* are both related to the surface heat flux, H_0 . Hence, only certain combinations of w_* and Z_i can occur.

The figures on page 103 present the data shown in the previous figure with a curve representing an empirical approximation to the upper bound on $w_* = w_{*max}$. To demonstrate the application of the calculation of worst-case meteorological conditions for convective boundary layers the upper bound curve shown on these figures was employed to define the range of plausible w_* given Z_i within the range 50 to 3000 m.

Pages 104-108 summarize for each source the results of the worst-case concentration calculations, c_w . The results are listed on copies of the figures shown on pages 97-101. In all cases the ambient temperature was assumed to be 15°C. For all sources considered the

worst-case meteorological conditions were determined to be convective. The critical meteorological conditions are summarized on the figures. In each case the combination of w_{*} and Z_i selected by the model while scanning the range of plausible values was w_{*max} for a value of Z_i which just exceeds the source height in the finite interval search through Z_i . This value of Z_i is selected because the proposed models do not permit penetration of the plume above Z_i . This aspect of the proposed models will be discussed in detail as an action item from the June 25-26 Modelling Workshop (pp. 110-126).

The worst-case modelling result for source #1 yields a maximum concentration of 240 concentration units. This is 27% higher than the annual maximum concentration calculated using hourly data. For source #2 the calculated worst-case concentration is 211 units. This is slightly less than the annual maximum (220) based on hourly calculations. The assumption that the ambient temperature is 15°C accounts for the underestimate by the worst-case. To demonstrate the sensitivity of this result to the assumed temperature the calculation was repeated for 30°C. In this case the worst-case concentration was 297 concentration units. It is proposed that it may be better to define the ambient temperature using climatological records for daytime maximum temperatures.

The predicted worst-case concentration of 216 units for source #3 exceeded the annual maximum by 8%. For source #4 the worst-case maximum was 219 concentration units. This exceeded the annual maximum concentration calculated using hourly data by approximately 16%. The worst-case concentration calculated for source #5 was 183 non-specific

concentration units. This exceeds the annual maximum determined using the full model by 9%.

In all cases tested the worst-case concentration calculated in a simplified manner compared closely with the full model package calculations. The resources required to complete the worst-case calculation are significantly less than those required by the hourly calculations.

6. SUMMARY OF WORKSHOP COMMENTS

The workshop attendees agreed that the proposed modelling package is acceptable on its scientific merit. The presentations on modelling results showed clearly the advantage of using these models over the existing models. However, several points were raised which should be clarified before the models are used in a regulatory framework. These are as follows:

1. More comparisons between existing models and the proposed models for different source configurations should be carried out.
2. The applicability of the models to the appropriate situations should be clearly defined.
3. The use of a background concentration in the application of the models to a single source in a distributed source situation should be clearly defined.
4. The models should not be rigidly defined in the Regulation. A formal mechanism to allow changes as science improves should be provided.
5. A safety factor should not be used. The statistical concept defining the probability that model generated worst-case simulation will be exceeded by observation should be given.
6. The Regulation should make provision for physical modelling for complex situations where modelling is difficult to implement.

7. It should be clearly defined what type of meteorological data should be used for multiple source situations.
8. The models should be evaluated for real life situations.
9. The modelling package should be peer-reviewed by scientists outside Ontario.
10. The modelling package should include a clear description of how long-term averages are computed.

Each of the ten items listed above have been reviewed by Ministry staff. In the order presented above, the following comments are offered:

1. The Ministry plans to continue evaluation of the proposed air quality models for various source configurations on a regular basis. Based on evaluations to date it is the Ministry's position that the proposed models represent a substantial improvement in the science of modelling as compared to Regulation 308.
2. The Ministry plans to produce a guideline which clearly sets out the steps required to apply the proposed air quality models.
3. The background concentration of commonly monitored contaminants may be obtained from measurements. To determine the background concentration of other contaminants air quality modelling for multiple source configurations will be necessary.

4. It would be advantageous for any new regulation for air management to include a simple, well-defined mechanism for updating the modelling techniques when better (scientifically credible and evaluated) models become available. However, the legal aspects of this remain to be reviewed by the Ministry.
5. It is recommended that neither safety factors nor estimates of expected deviations of the model results from observations be used when applying the proposed models for regulatory applications.
6. The need to apply physical modelling for complex terrain and complicated building structure situations is acknowledged. Physical modelling should be carried out in a manner which preserves atmospheric scaling relationships. The Ministry has prepared provisional guidelines for modelling air quality on or near structures and in complex settings.
7. Meteorological data will be made available to the public in the same format as received on the Ministry's Meteorological Data Acquisition System (MDAS).
8. Data are not readily available for evaluating the models for 'real life' situations (pp. 46-51).
9. The proposed models have been published in refereed international journals, undergoing the required scientific review. The Ministry continues to encourage more scientific review.

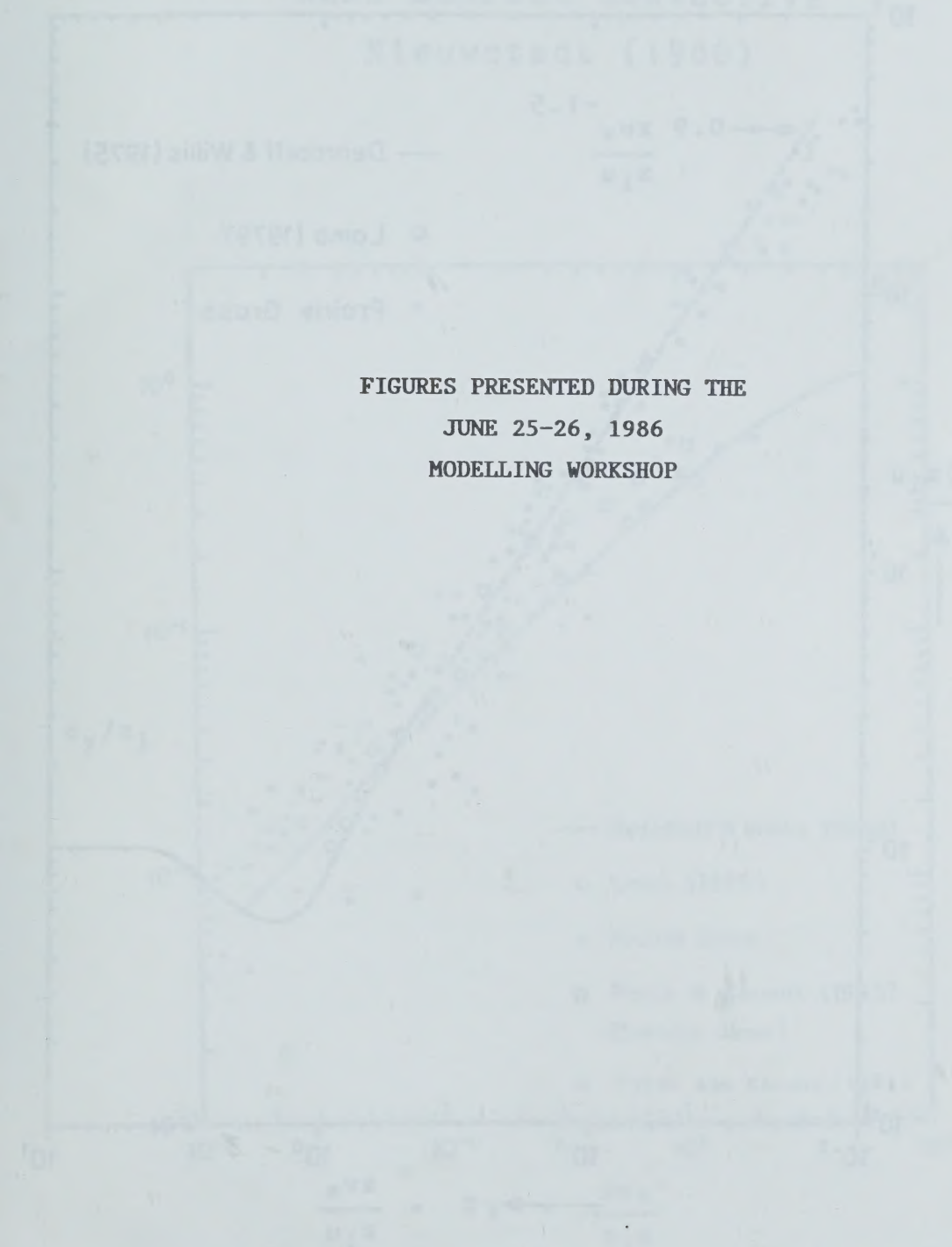
10. It is recommended that contaminant air concentrations for periods exceeding a one-hour averaging time be generated by averaging sequences of one-hour average concentrations to develop the long-term average. Statistical methods for estimating 24-hour, annual and longer term averages are being reviewed.

Aside from the above comments some minor action items were identified. A response on one action item on plume penetration is to be found on pages 111-126. At present no plume penetration models which met the selection criteria outlined in this report are available. Hence, it is recommended by the Ministry that Manins simple plume penetration model be employed with $\Delta\theta=10^{\circ}\text{C}$ until a more suitable model is available.

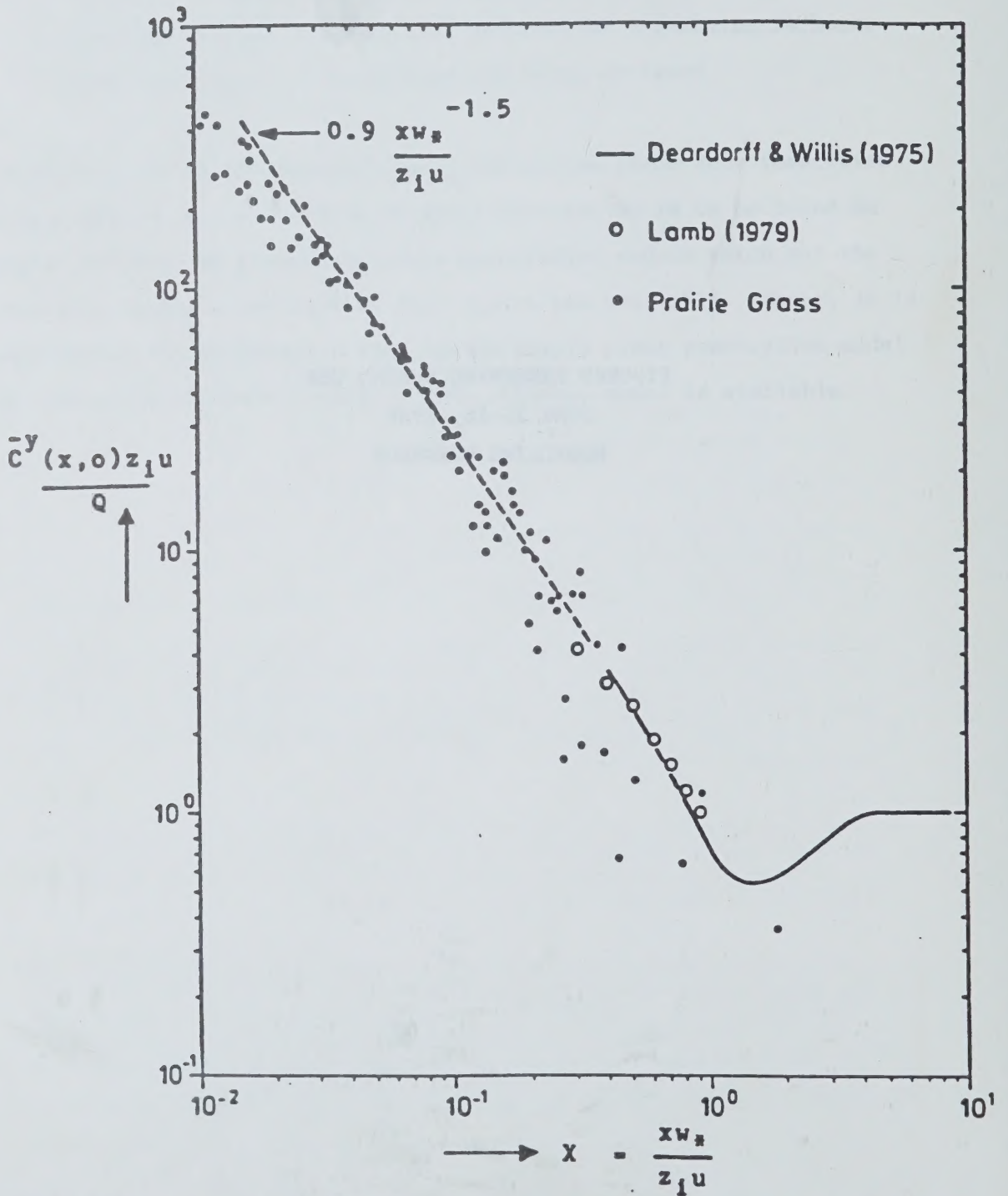
NEAR SURFACE CONVECTIVE WINDS (1980)

NEAR SURFACE CONVECTIVE WINDS (1980)

FIGURES PRESENTED DURING THE
JUNE 25-26, 1986
MODELLING WORKSHOP

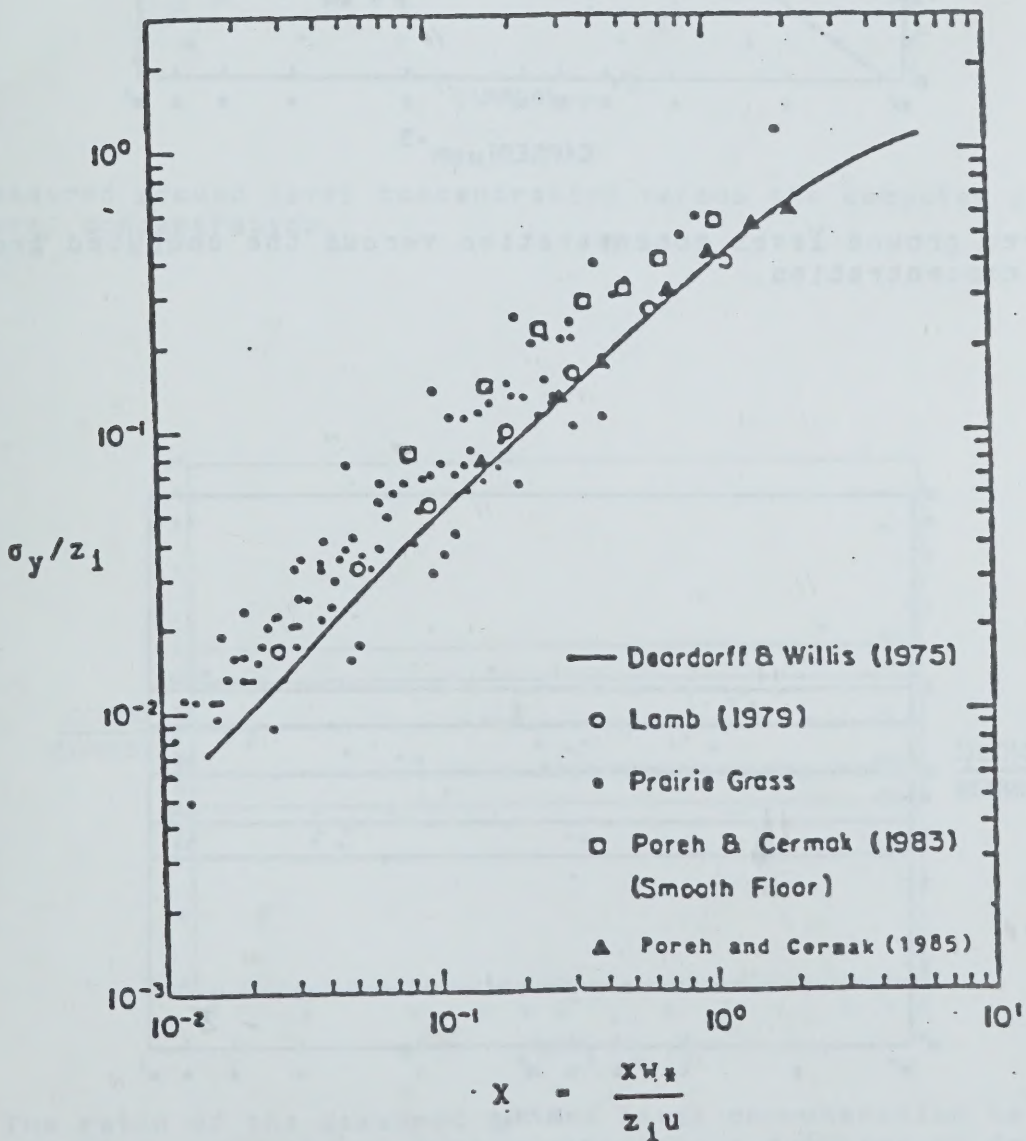


NEAR SURFACE CONVECTIVE Nieuwstadt (1980)



Dimensionless cross-wind integrated concentration at ground level as a function of the mixed-layer scaling variable X .

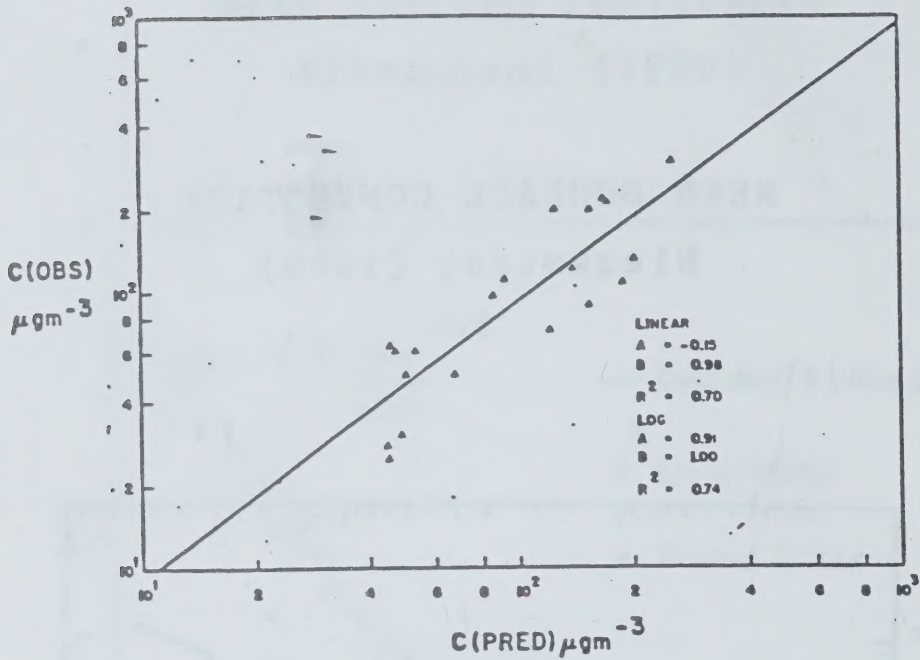
NEAR SURFACE CONVECTIVE Nieuwstadt (1980)



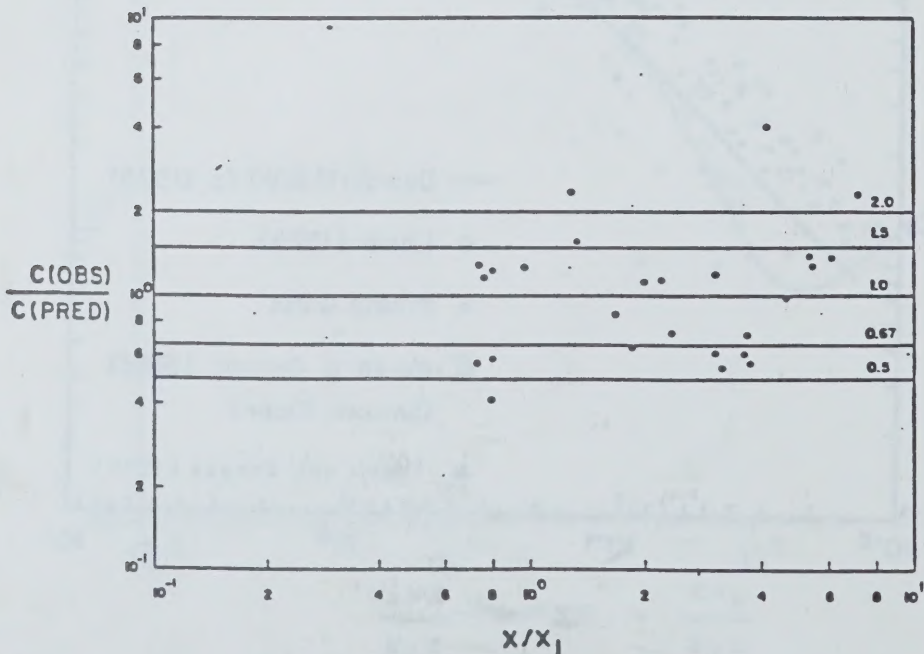
Data on the non-dimensional horizontal dispersion parameter σ_y/z_1 versus X .

ELEVATED CONVECTIVE Venkatram (1980)

DICKERSON MOBILE VAN MEASUREMENTS



Measured ground level concentration versus the computed ground level concentration.

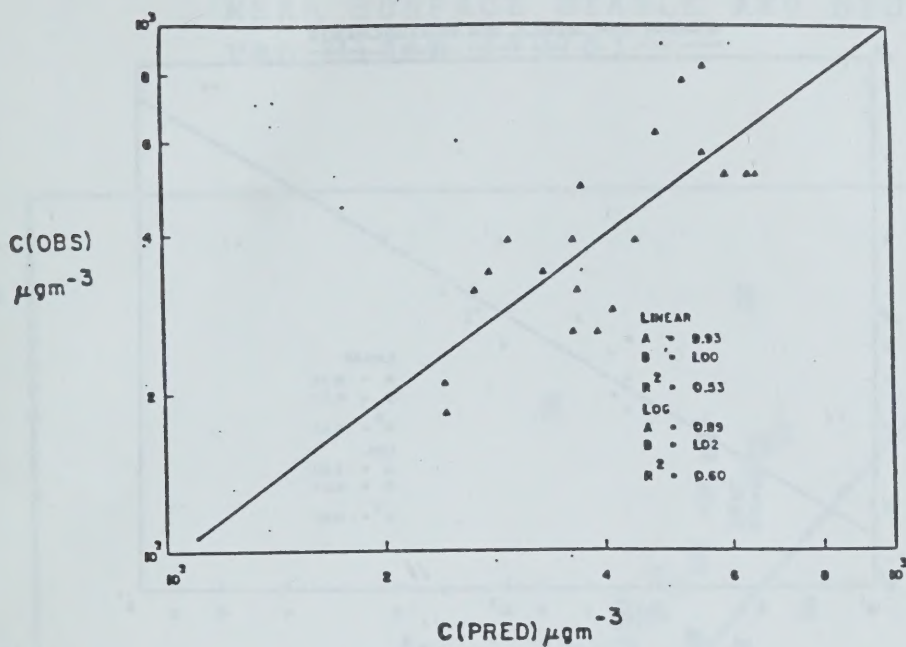


The ratio of the measured ground level concentration to the modelled ground level concentration as a function of downwind distance non-dimensionalized by the calculated most probable point of impingement (X_1).

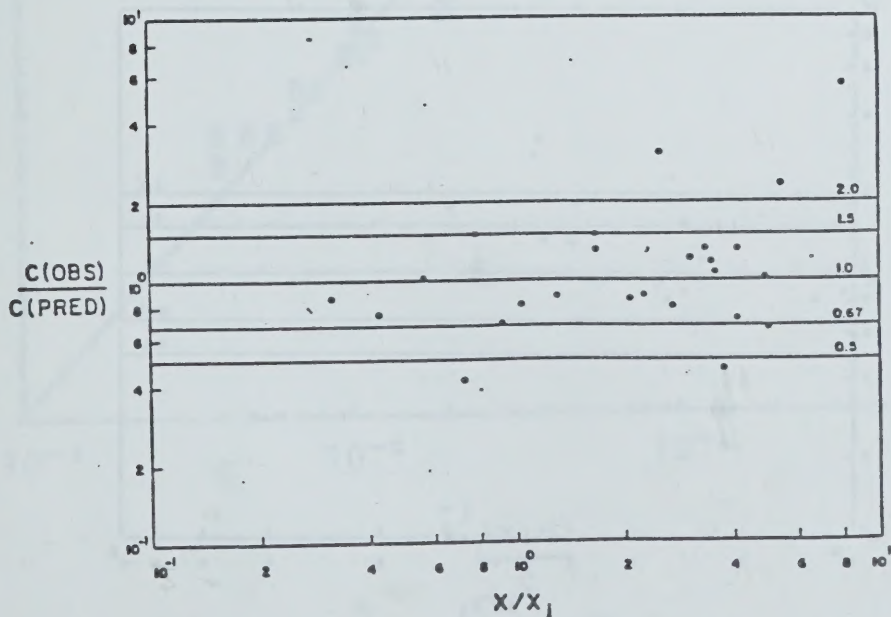
ELEVATED CONVECTIVE Venkatram (1980)

-71-

SUDBURY ENVIRONMENTAL STUDY

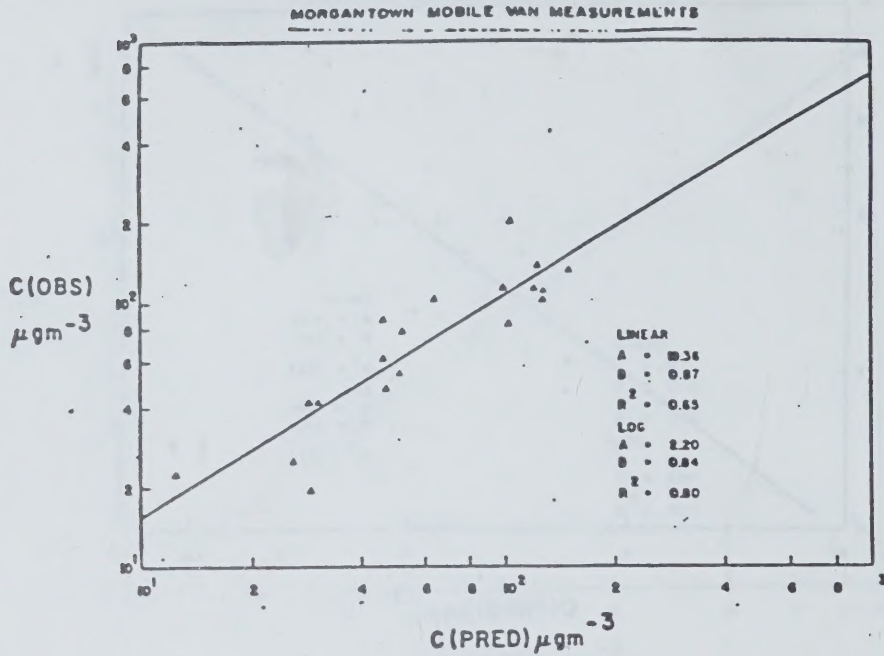


Measured ground level concentration versus the computed ground level concentration.

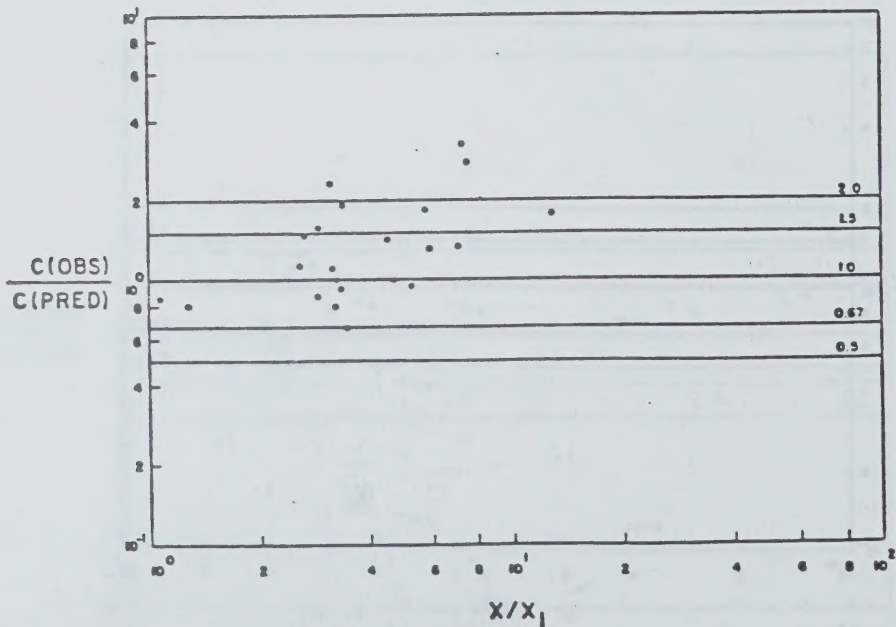


The ratio of the measured ground level concentration to the modelled ground level concentration as a function of downwind distance non-dimensionalized by the calculated most probable point of impingement (X_1).

ELEVATED CONVECTIVE Venkatram (1980)

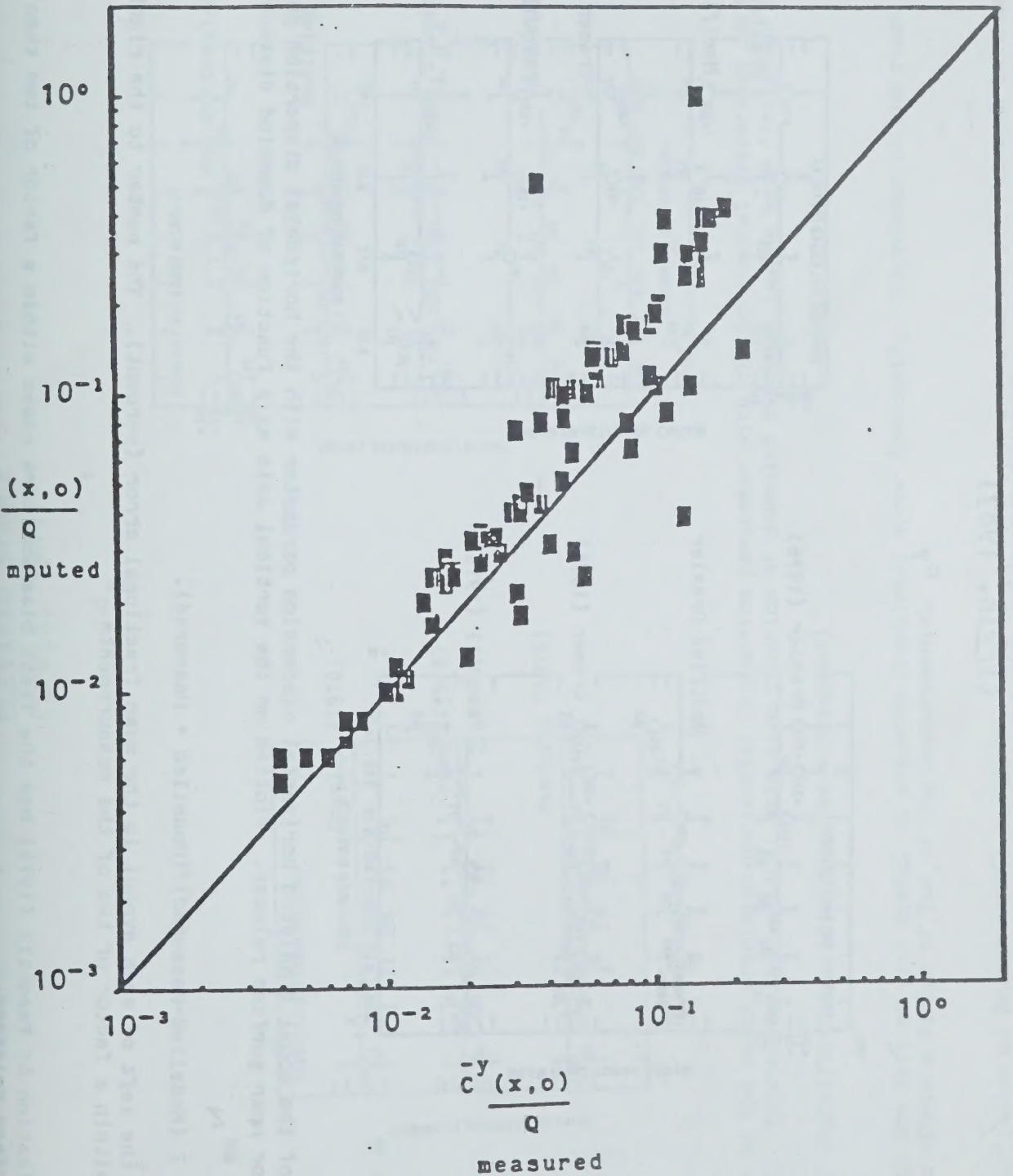


Measured ground level concentration versus the computed ground level concentration.



The ratio of the measured ground level concentration to the modelled ground level concentration as a function of downwind distance non-dimensionalized by the calculated most probable point of impingement (X_1).

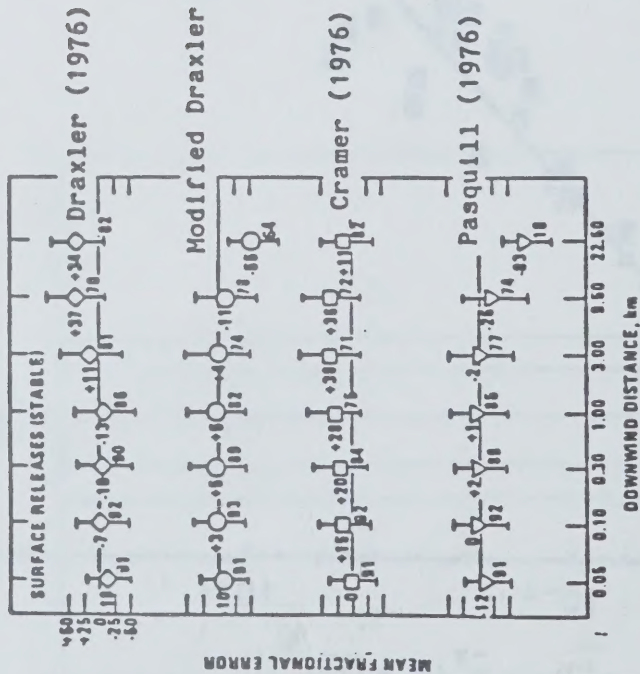
NEAR SURFACE STABLE AND NEUTRAL van Ulden (1978)



Computed cross-wind integrated concentration at ground level per unit emission versus the cross-wind integrated measured concentration per unit emission.

NEAR SURFACE STABLE (Irwin, 1983)

σ_y

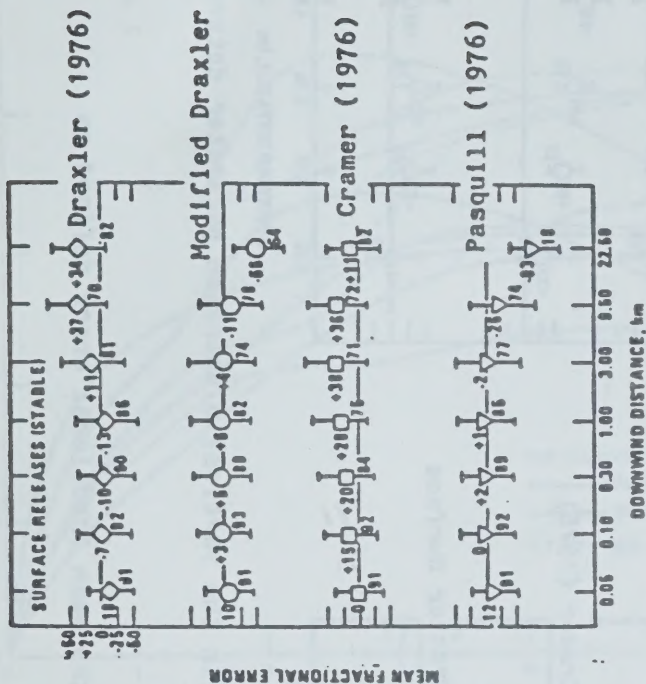
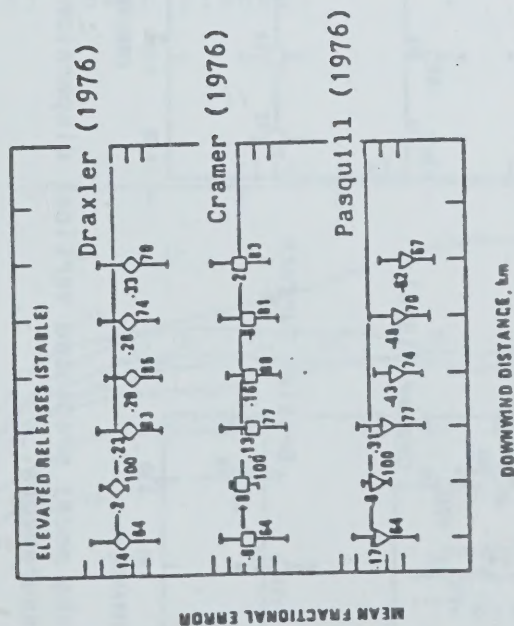


E - 2 (Modelled-Measured)/(Modelled + Measured).

The number to the left of each symbol is the mean fractional error (percent). The number to the right is the percentage of model values within a factor of two of the measurements.

The parameterization of Pasquill (1976) has the least bias and more cases within a factor of two than the other models Irwin tested for surface releases.

σ_y



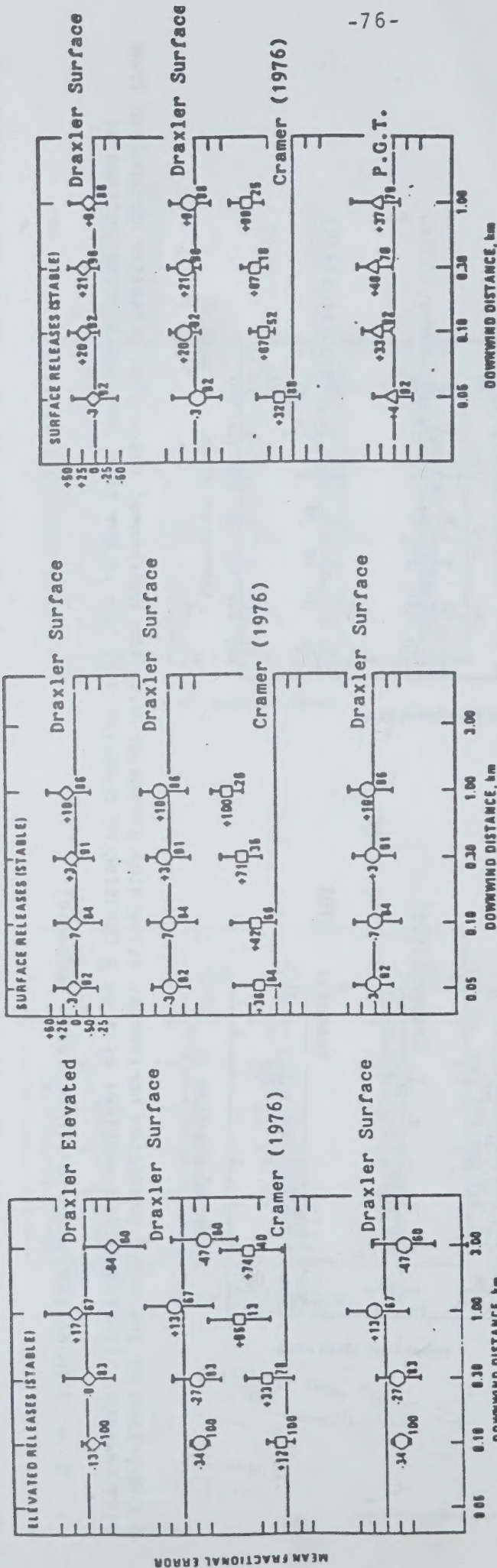
$$E = 2 \frac{(\text{Modelled} - \text{Measured})}{(\text{Modelled} + \text{Measured})}$$

The number to the left of each symbol is the mean fractional error (percent). The number to the right is the percentage of model values within a factor of two of the measurements.

The parameterization of Cramer (1976) yields the best comparison with measurements for releases between approximately 10 to 250 m. The release height criterion proposed to define elevated releases is that their release heights be greater than $L/50$. Hence releases below 10 meters may be classified as elevated. Pasquill's (1976) model performed better for the lower release heights.

ELEVATED STABLE (Irwin, 1983)

σ_z



A comparison of the model predicted vertical dispersion parameter with the vertical dispersion parameter determined from concentration measurements.

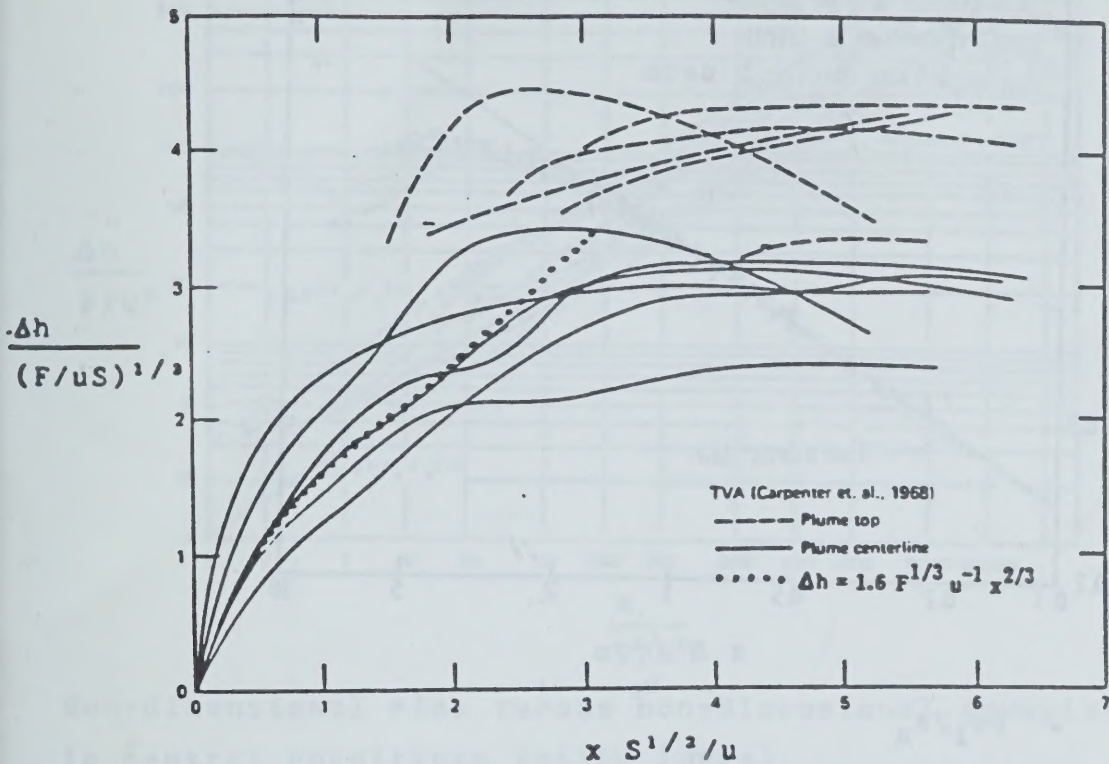
Plotted on the vertical axis as a function of downwind distance is the mean fractional error defined as

$$E = 2 \frac{(\text{Modelled} - \text{Measured})}{(\text{Modelled} + \text{Measured})}$$

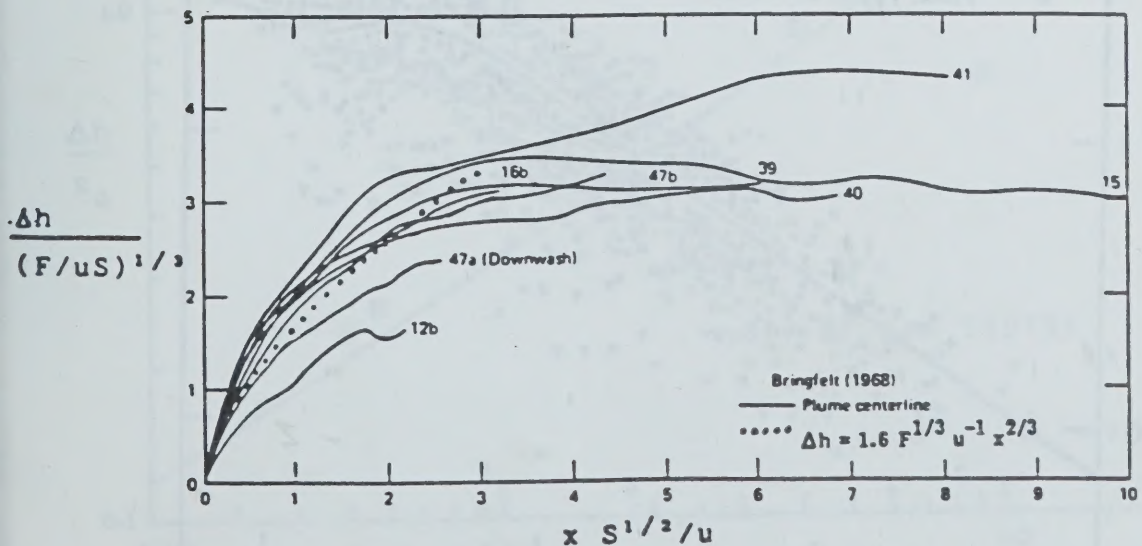
The number to the left of each symbol is the mean fractional error (percent). The number to the right is the percentage of model values within a factor of two of the measurements.

Irwin (1976) yields the best comparison with values based on measurements.

PLUME RISE IN STABLE AIR (Briggs, 1975)



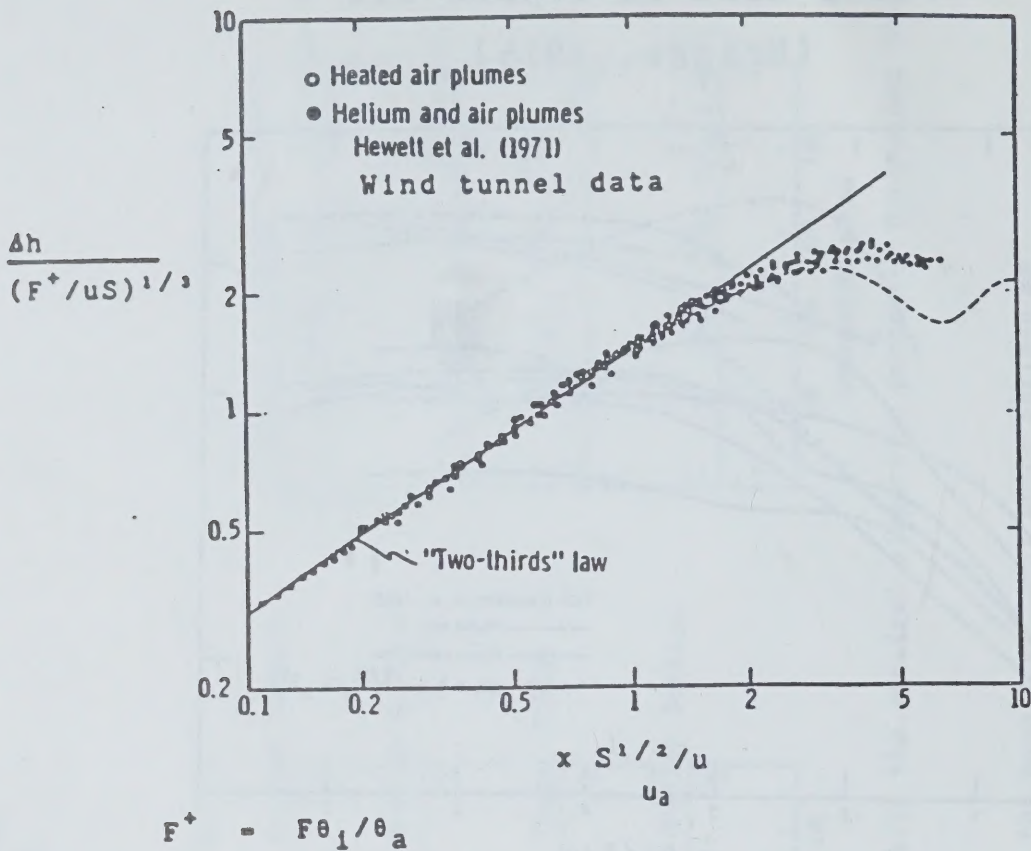
Non-dimensional rise versus non-dimensional downwind distance in stable conditions for measurements at Tennessee Valley Authority (TVA) power plants.



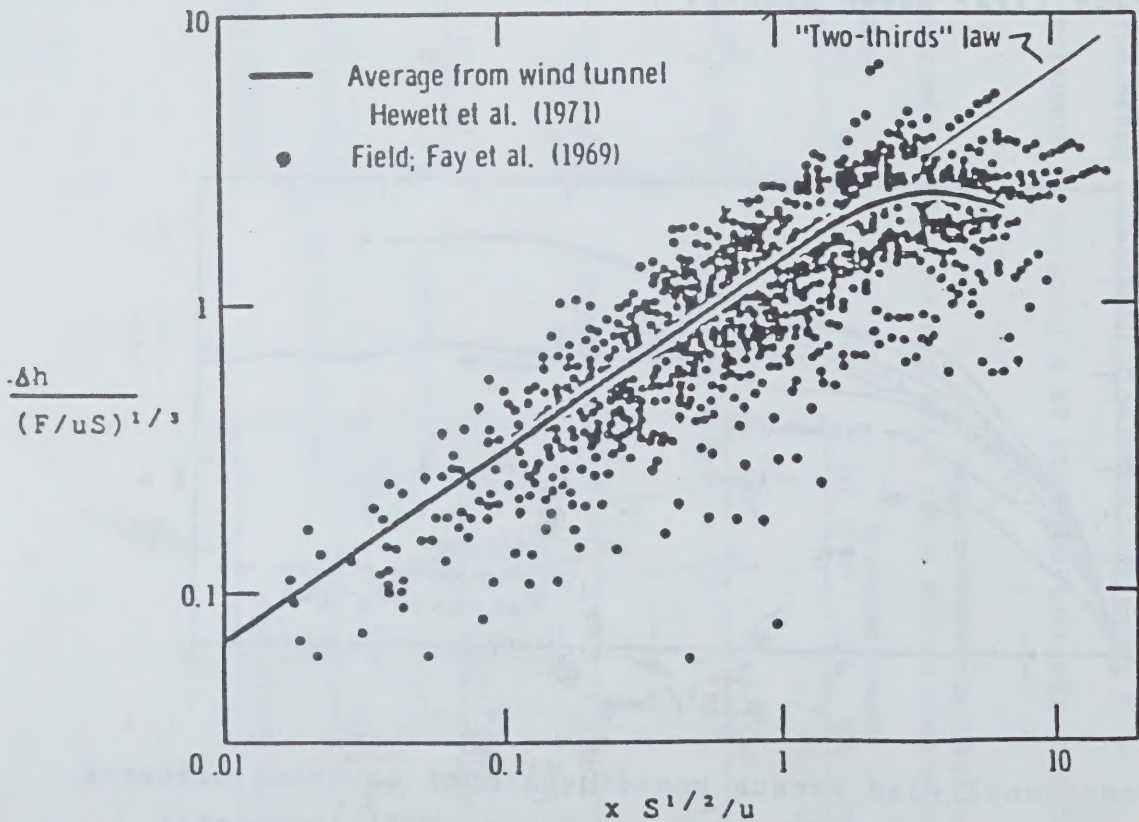
Non-dimensional rise versus non-dimensional downwind distance in stable conditions for measurements at small industrial sources.

PLUME RISE IN STABLE AIR (Briggs, 1975)

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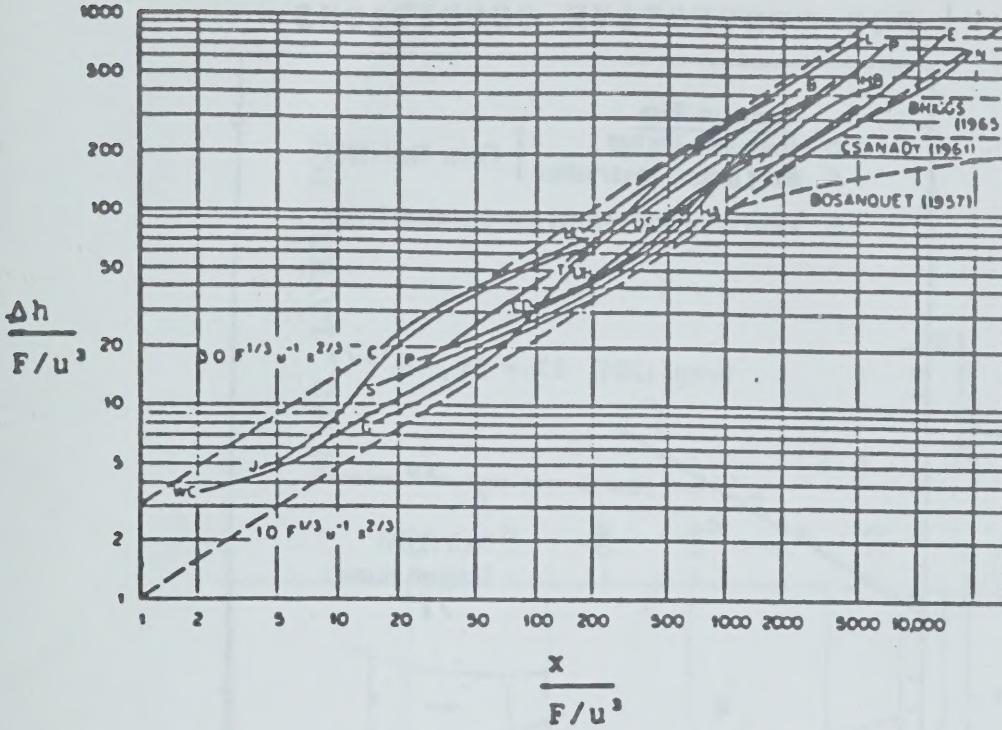


Non-dimensional rise versus non-dimensional downwind distance
in stable conditions.

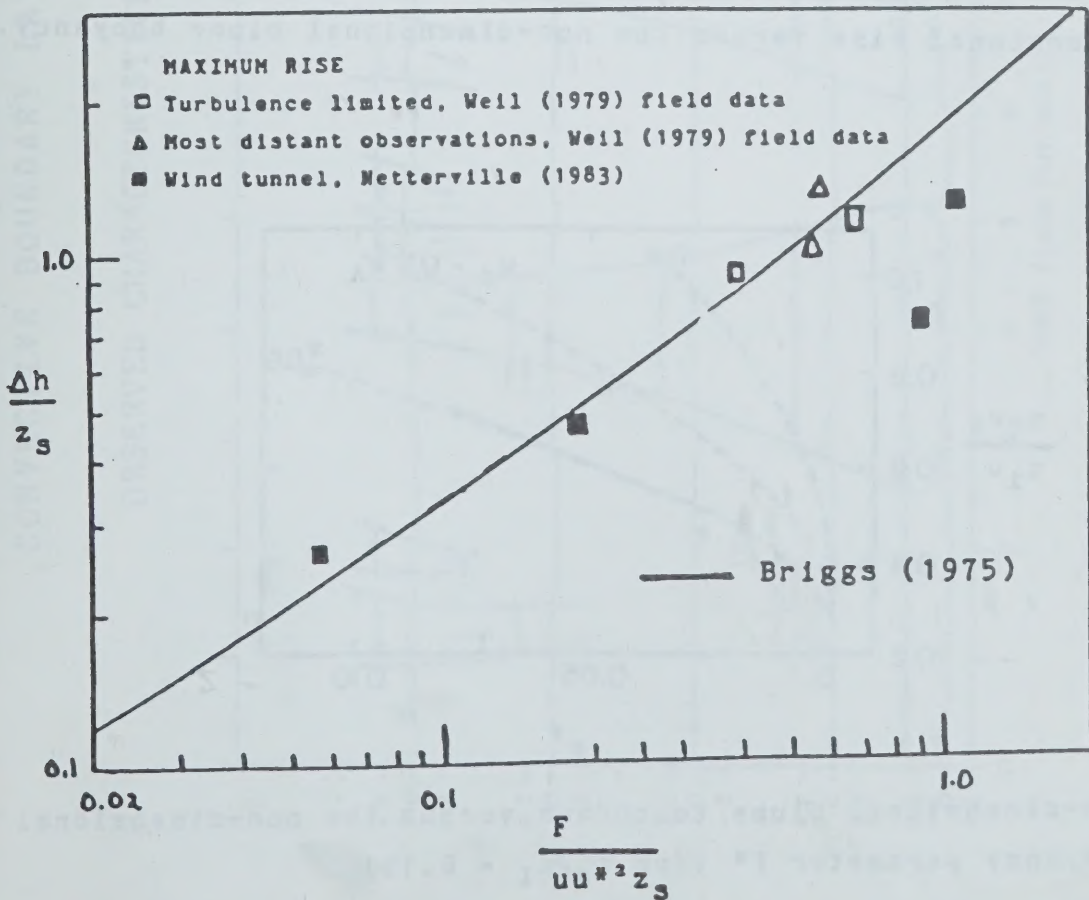


Non-dimensional rise versus non-dimensional downwind distance
in stable conditions.

PLUME RISE IN NEUTRAL CONDITIONS

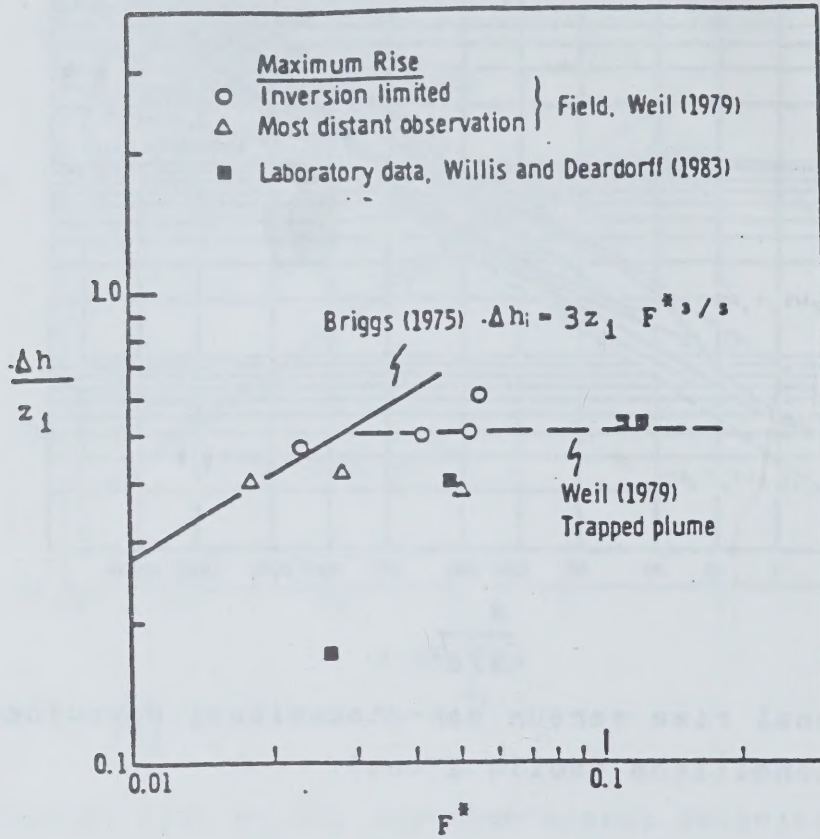


Non-dimensional rise versus non-dimensional downwind distance in neutral conditions (solid lines).

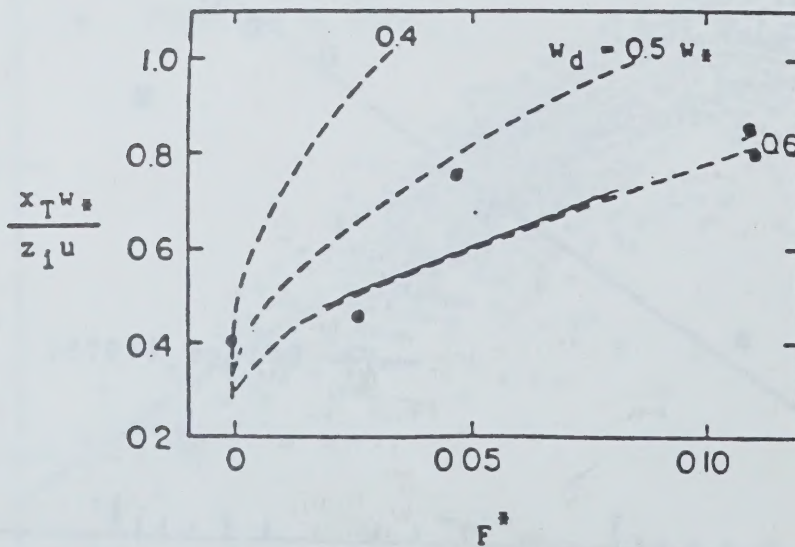


Rise versus non-dimensional buoyancy in neutral conditions.

PLUME RISE CONSIDERATIONS FOR CONVECTIVE CONDITIONS



Non-dimensional rise versus the non-dimensional plume buoyancy.

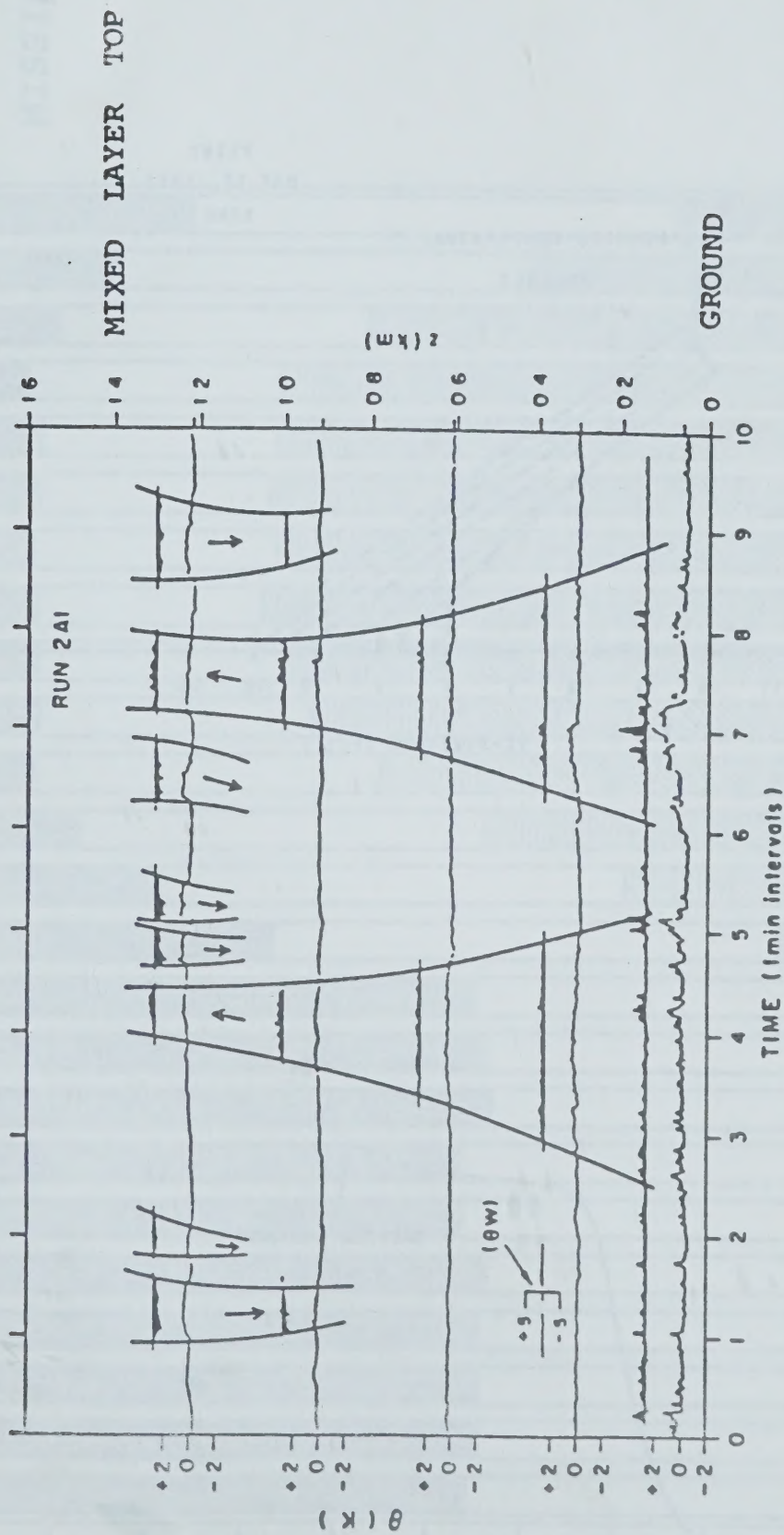


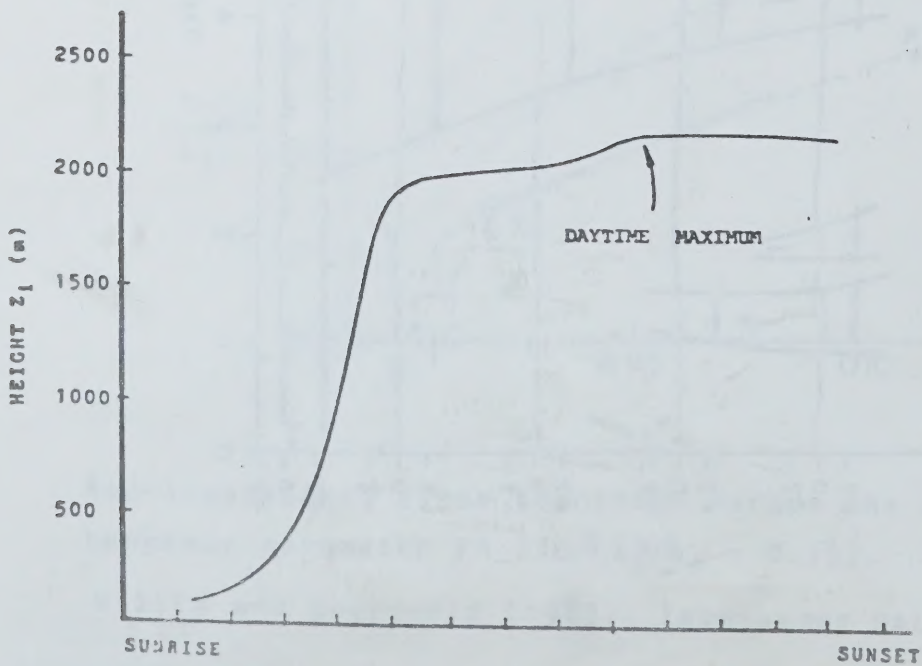
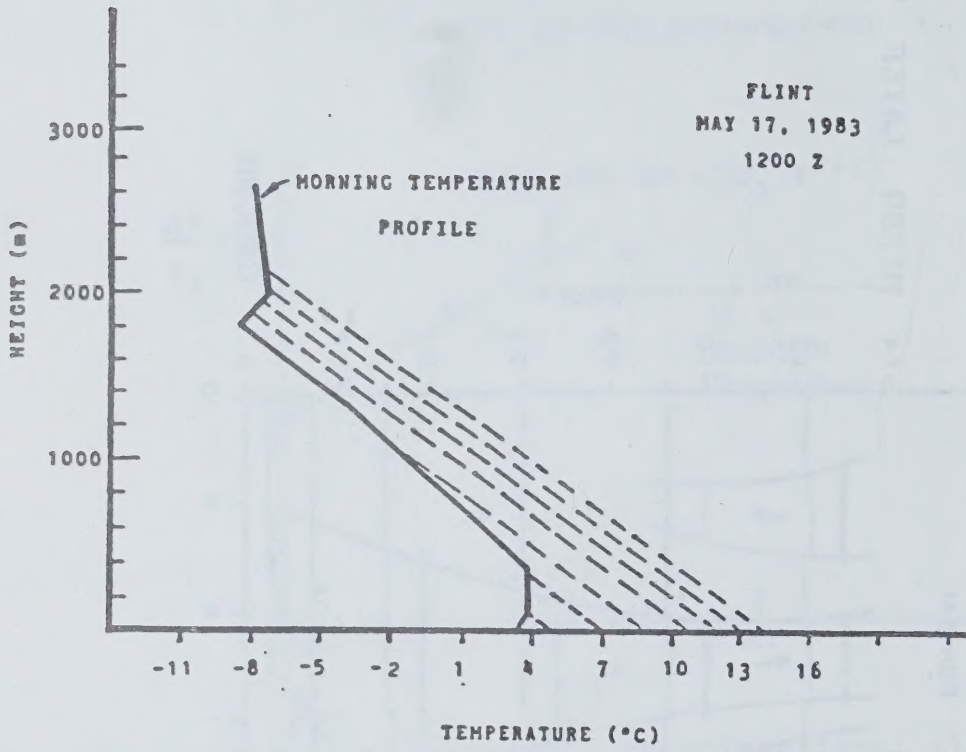
Non-dimensional plume touchdown versus the non-dimensional buoyancy parameter F^* (for $z_s/z_1 = 0.15$).

Willis and Deardorff (1983), laboratory data

CONVECTIVE BOUNDARY LAYER

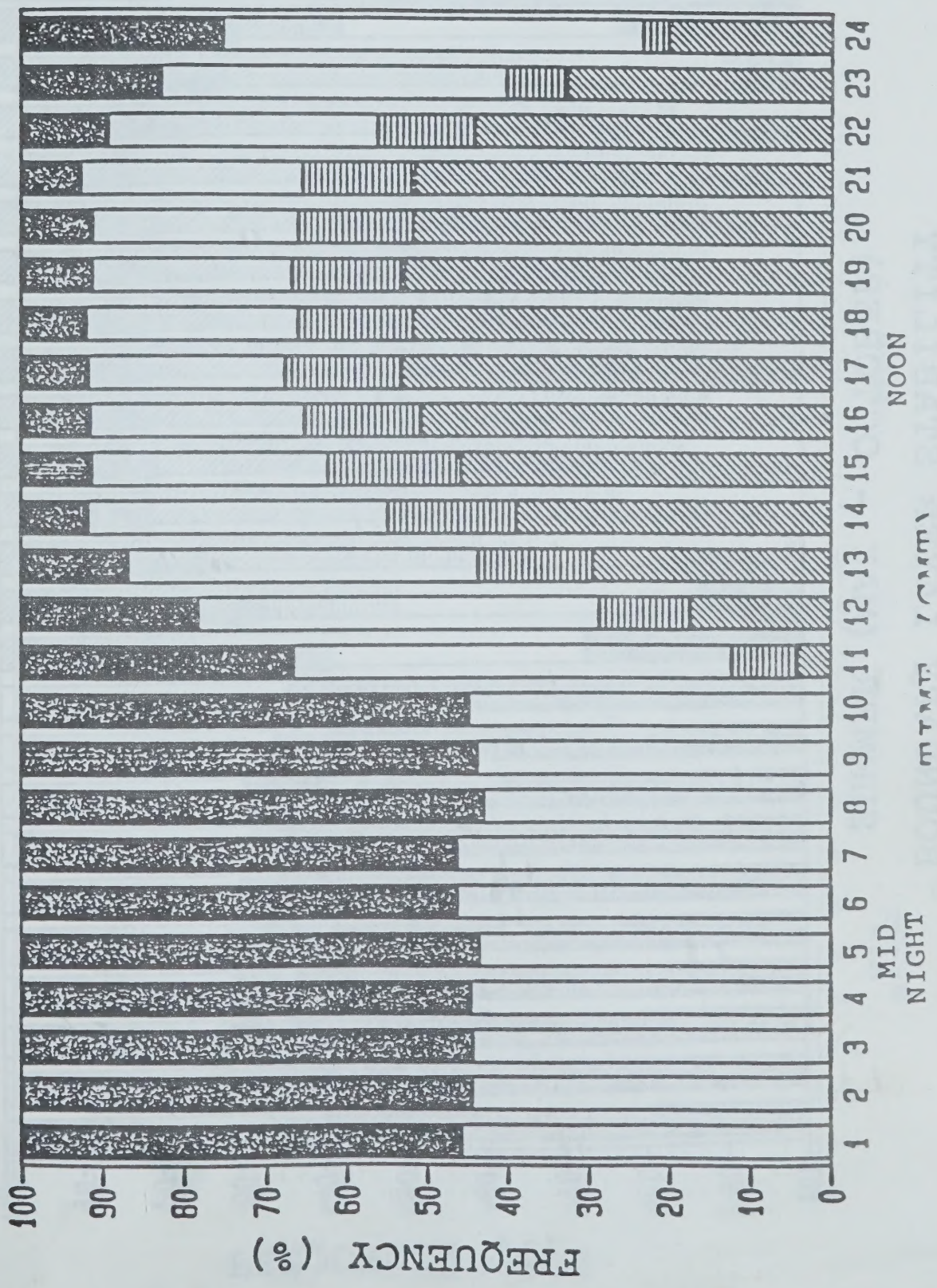
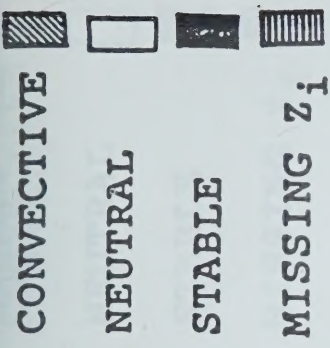
OBSERVED CHARACTERISTICS





BOUNDARY LAYER STABILITY

1983 ANNUAL



CONVECTIVE

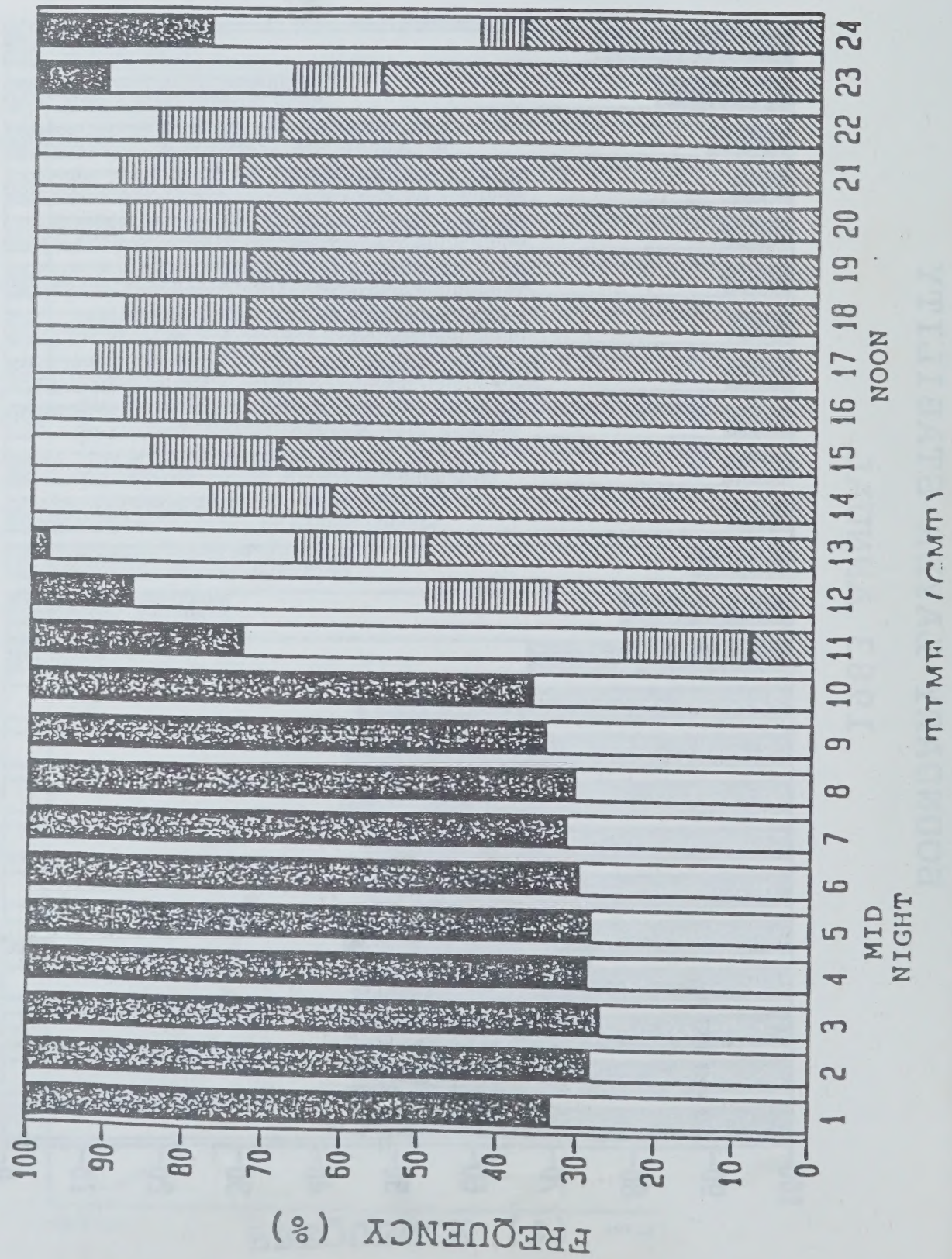
NEUTRAL

STABLE

MISSING z_i

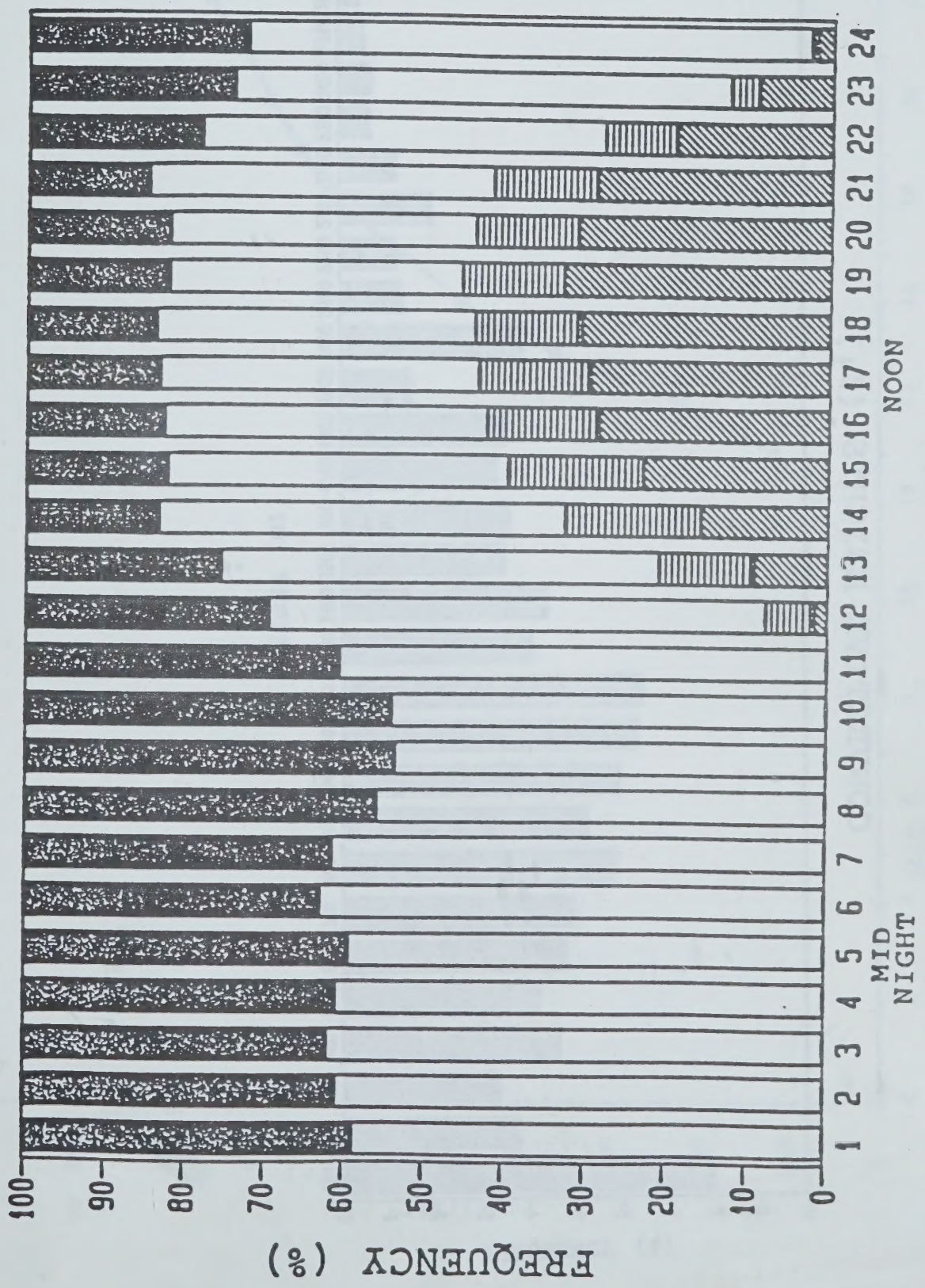
BOUNDARY LAYER STABILITY

SUMMER (MAY - OCTOBER)

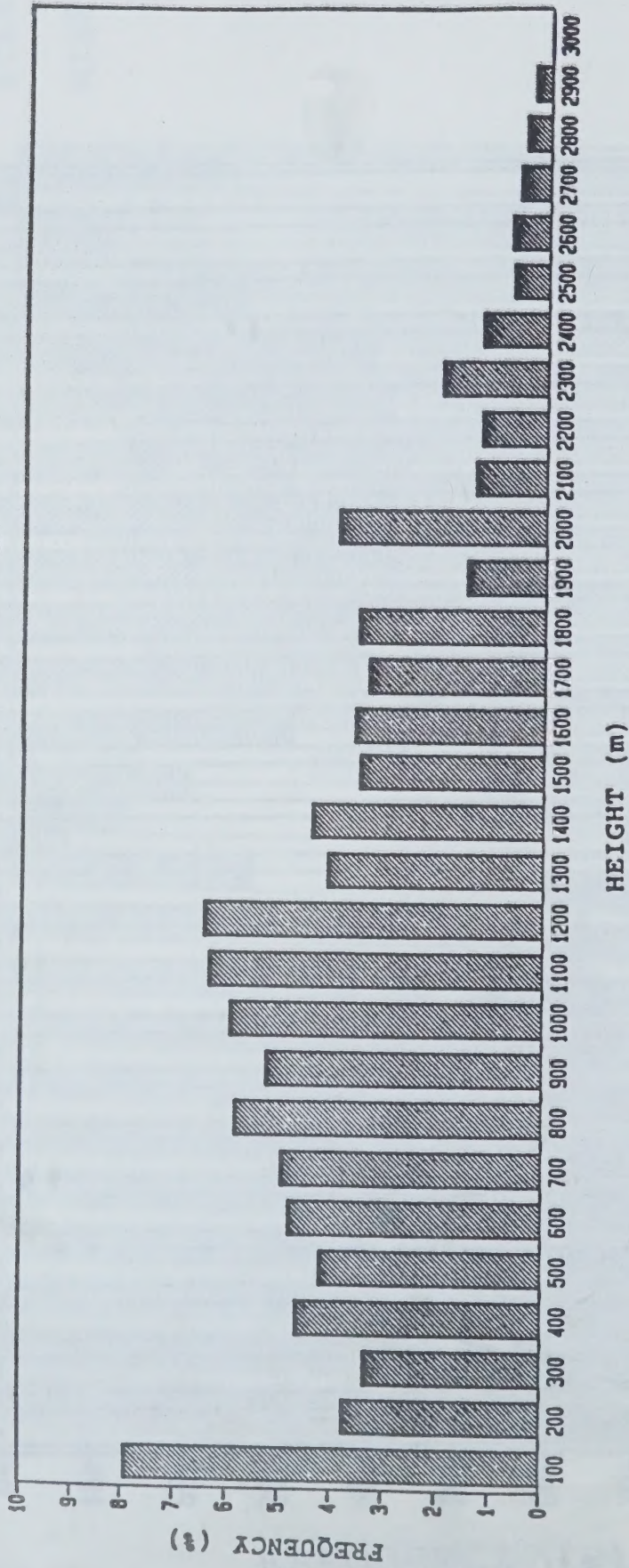


BOUNDARY LAYER STABILITY WINTER (NOVEMBER - APRIL)

CONVECTIVE
NEUTRAL
STABLE
MISSING z_i

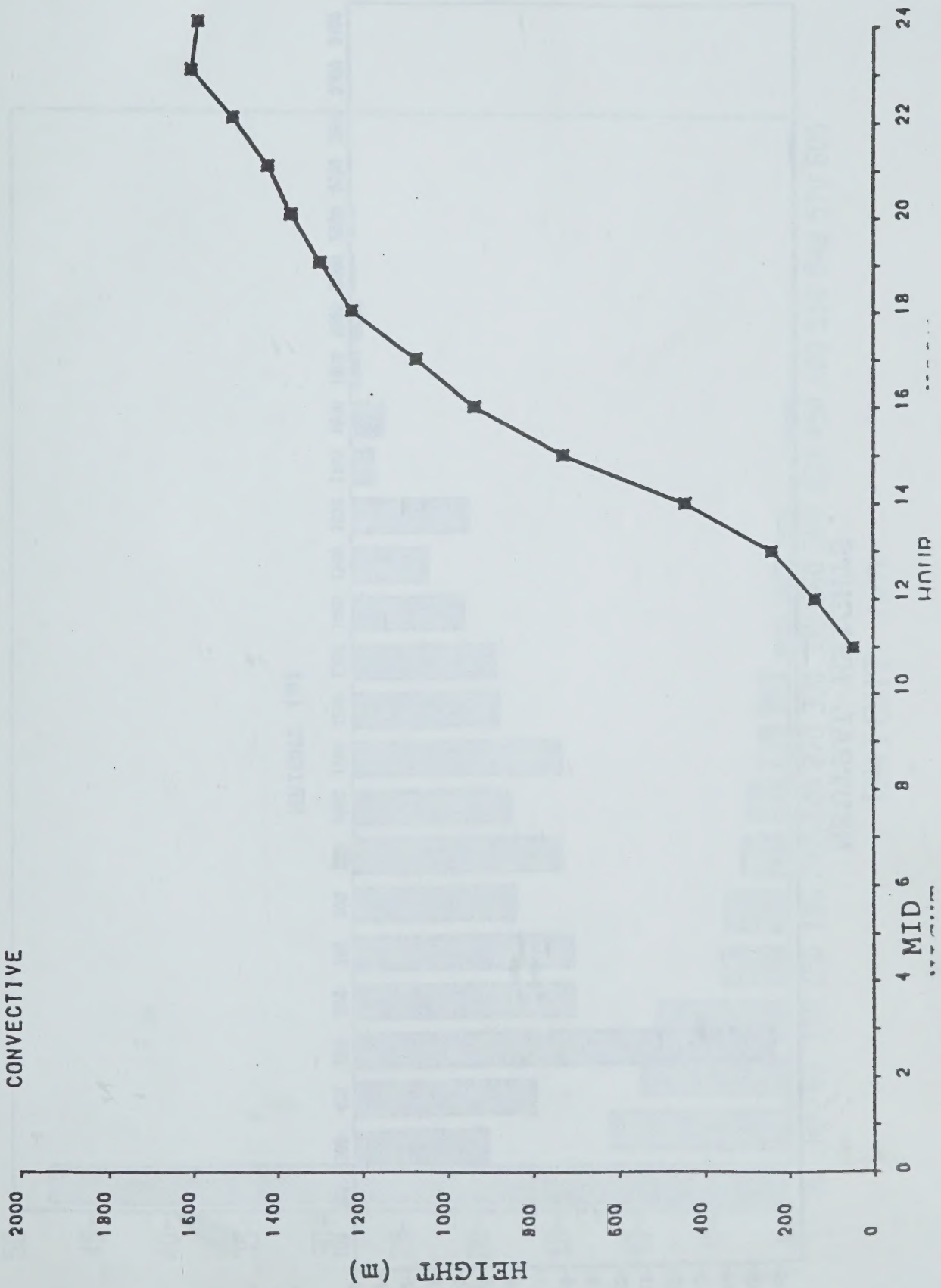


CONVECTIVE HEIGHTS (z_i)

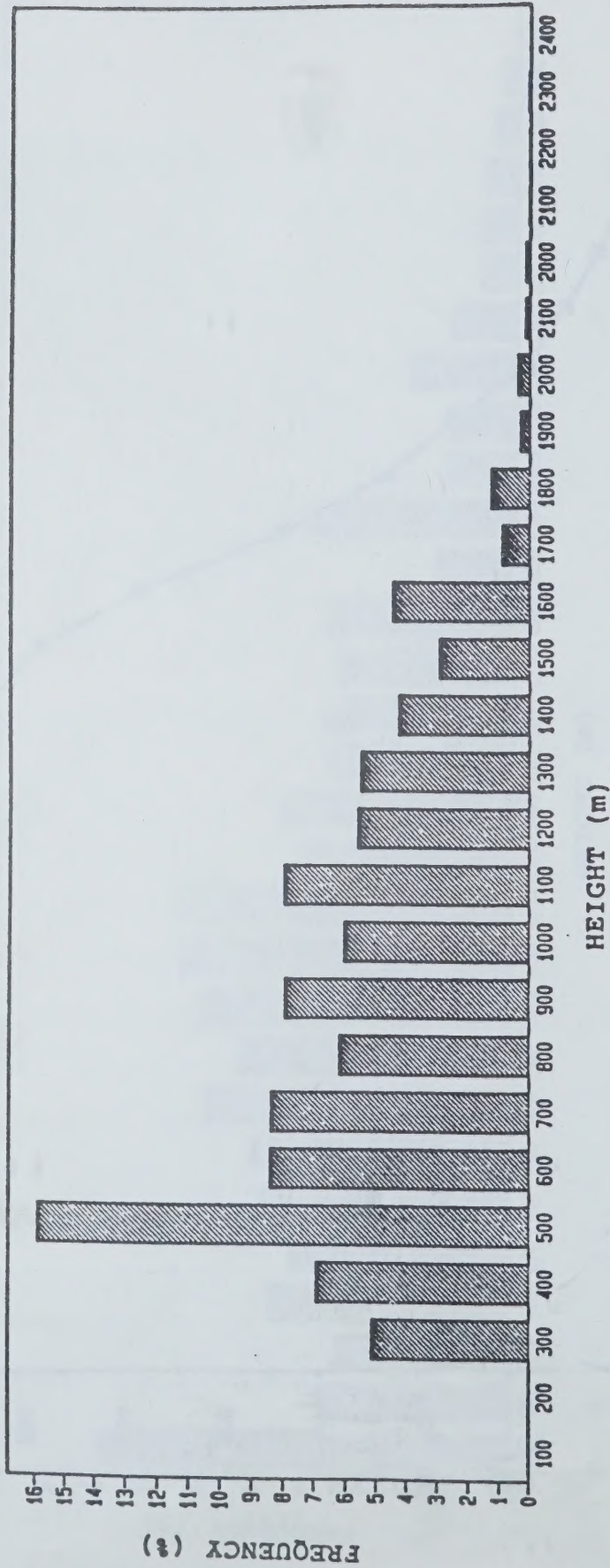


HOUR VS ZI

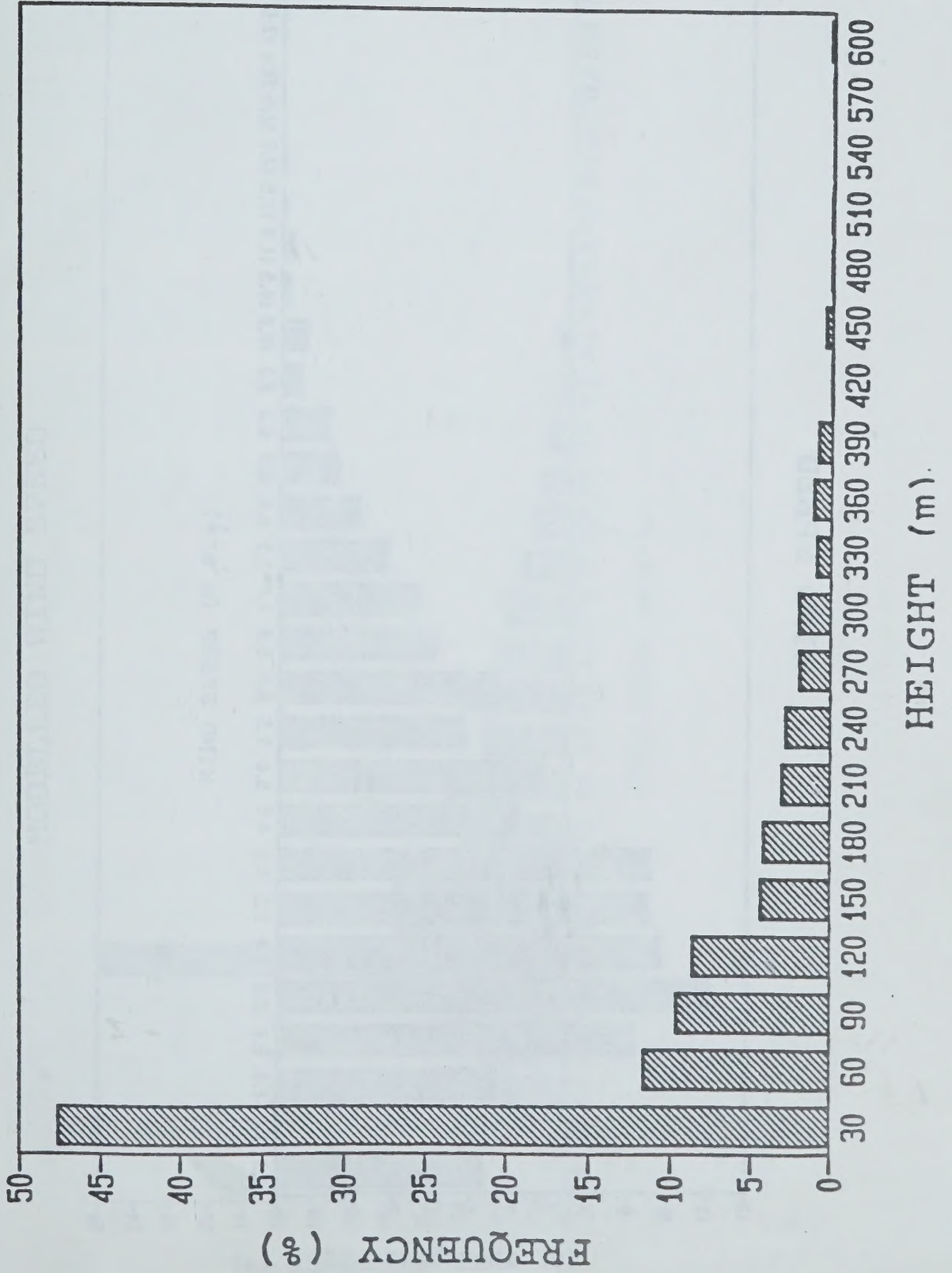
CONVECTIVE



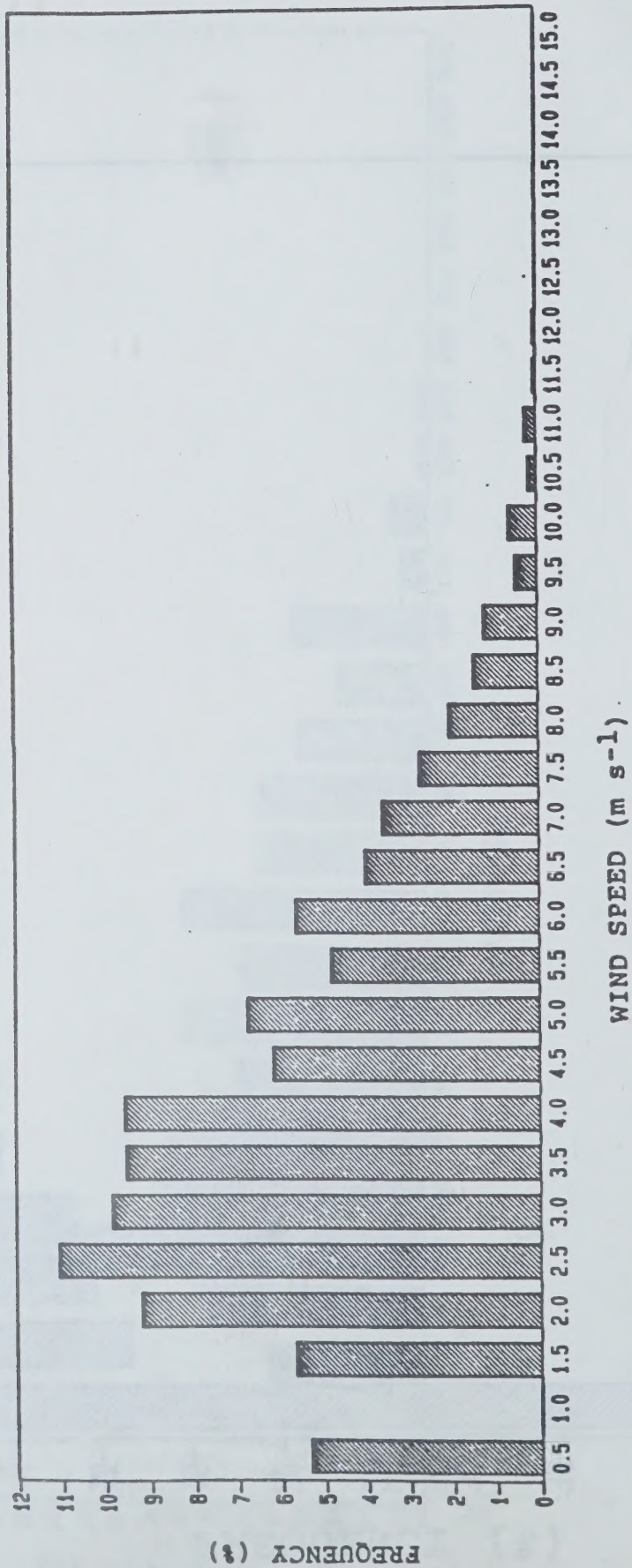
NEUTRAL HEIGHTS



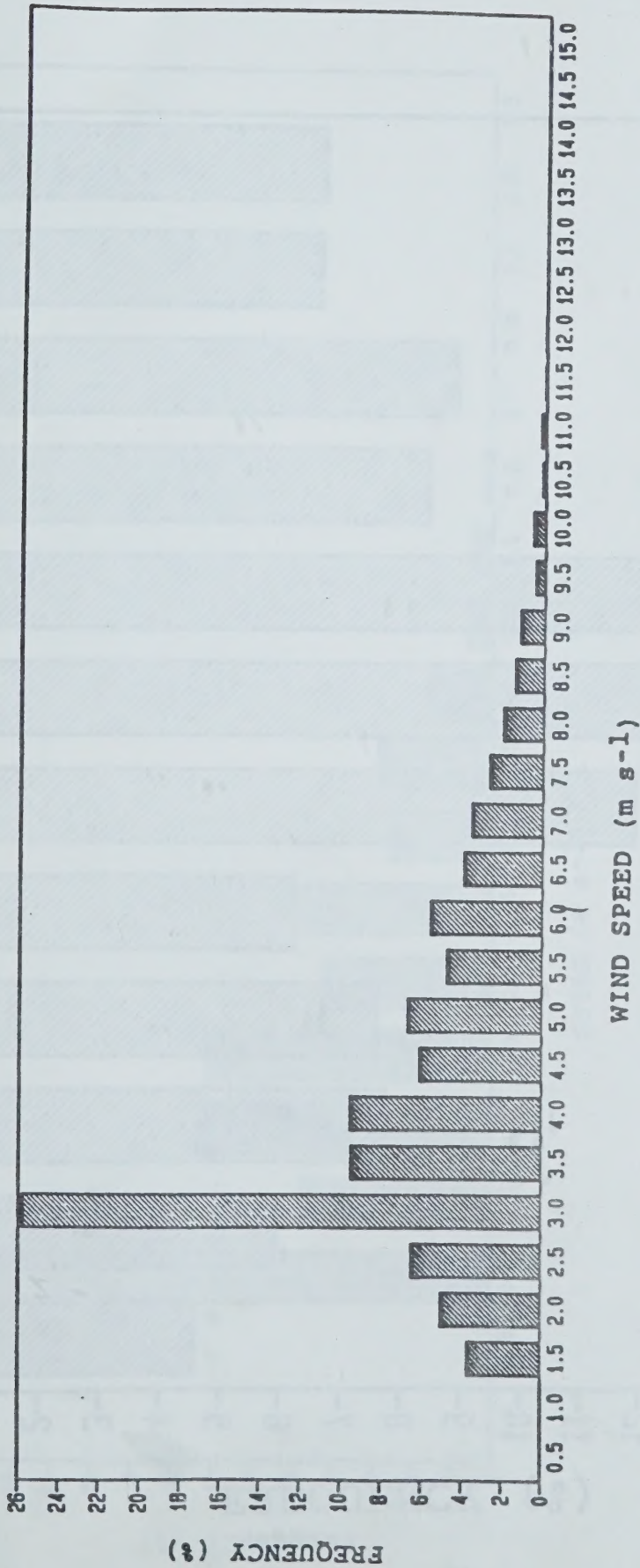
STABLE HEIGHTS



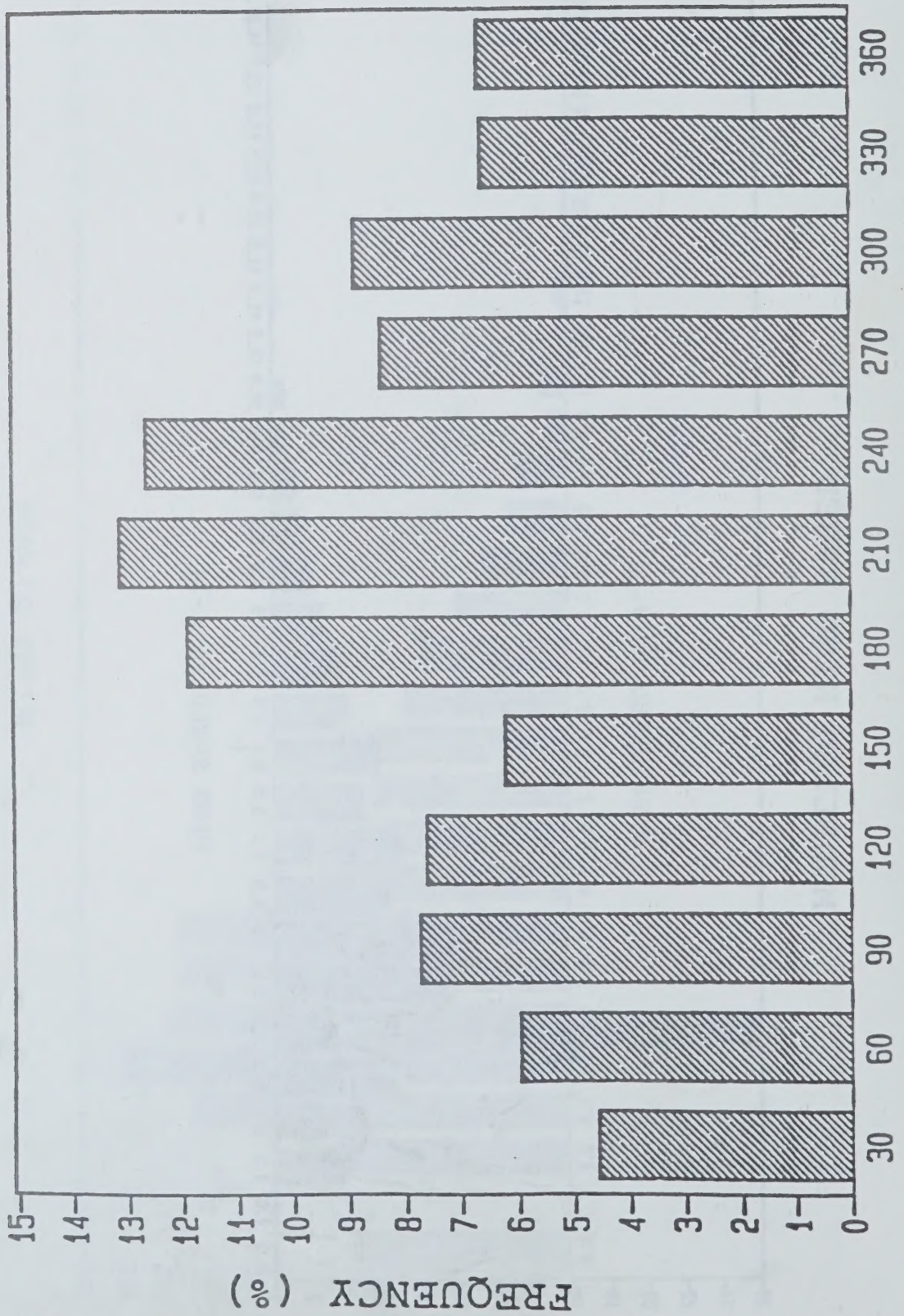
WIND SPEED



MODELLED WIND SPEED

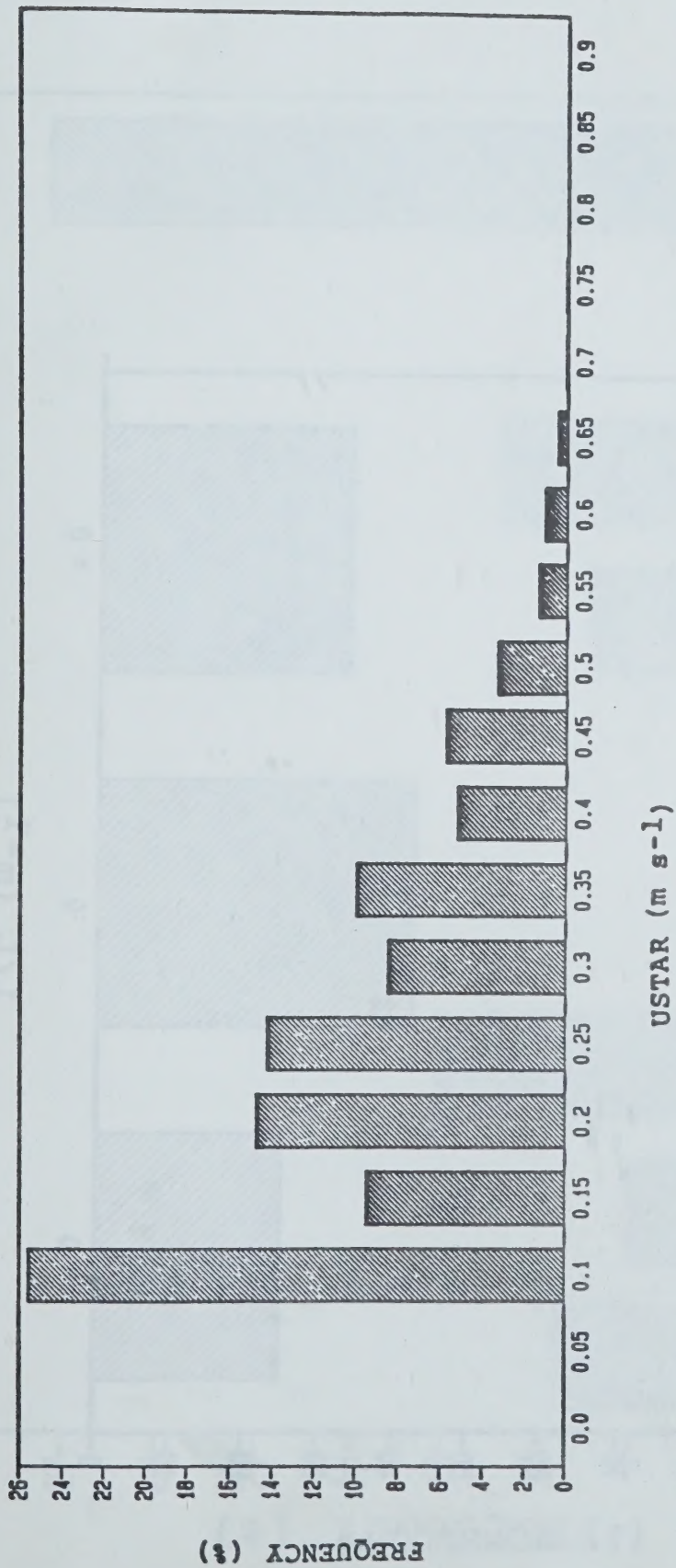


WIND DIRECTION

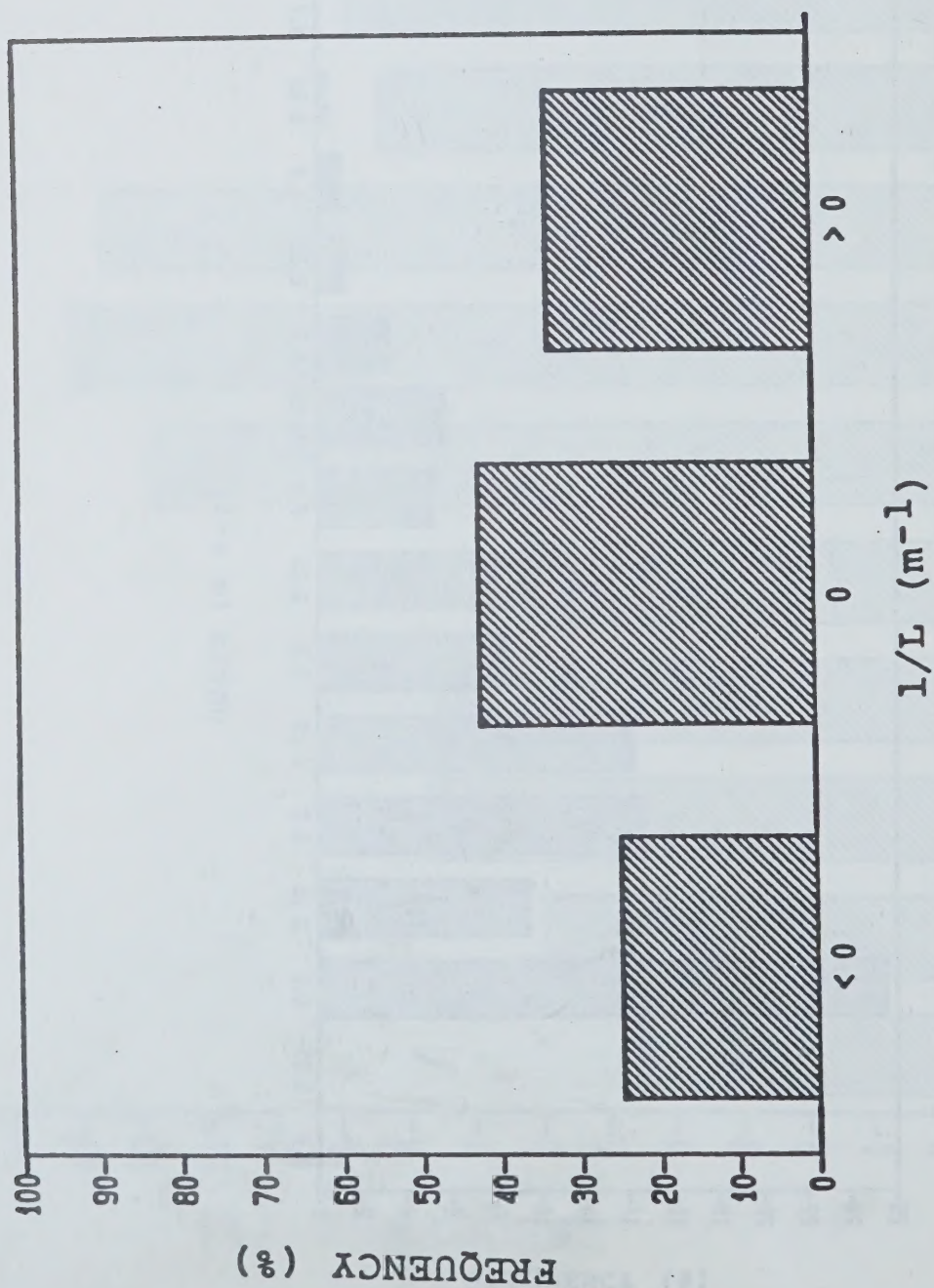


WIND DIRECTION (DEGREES)

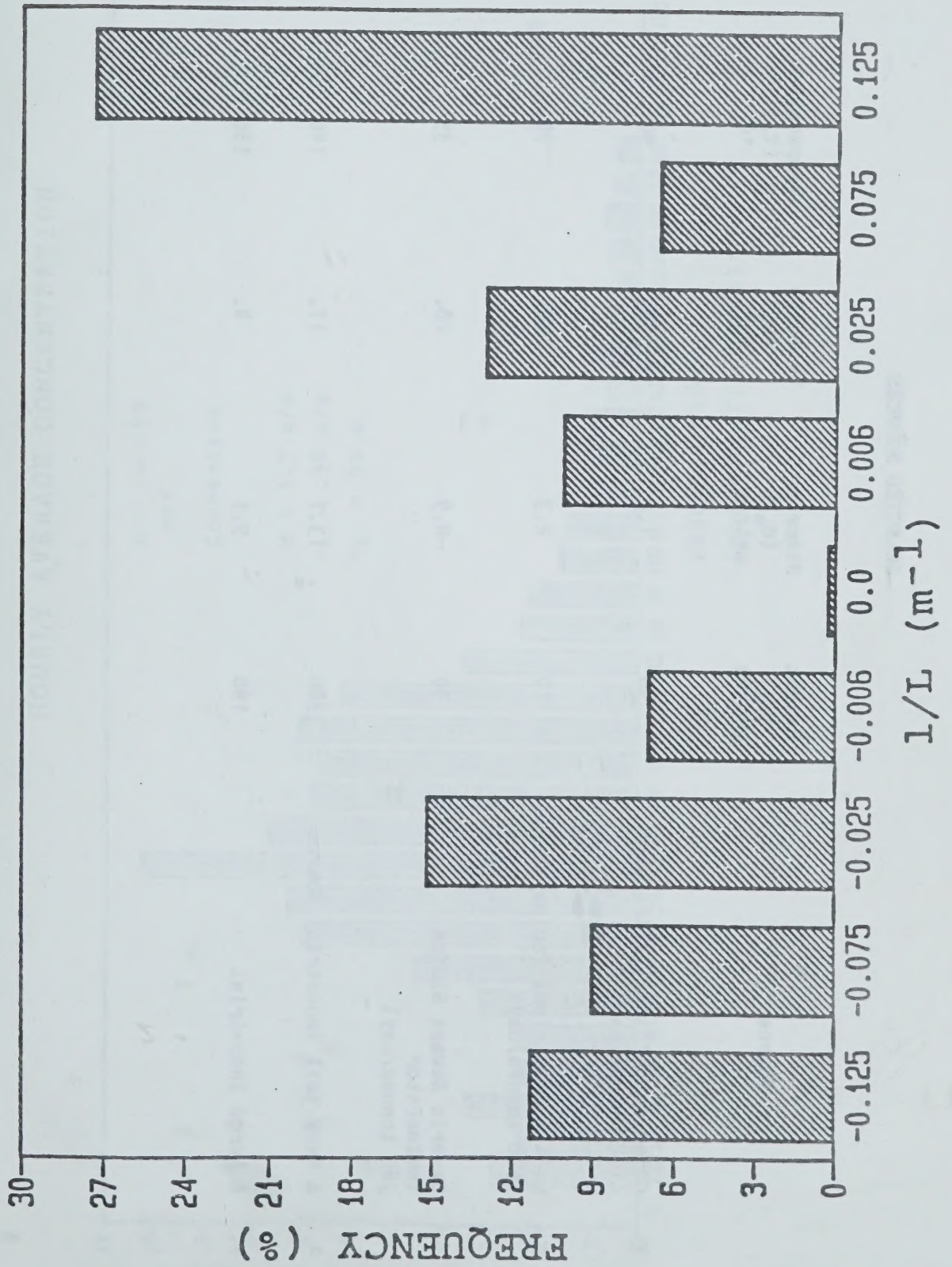
USTAR



BOUNDARY LAYER STABILITY



I/L

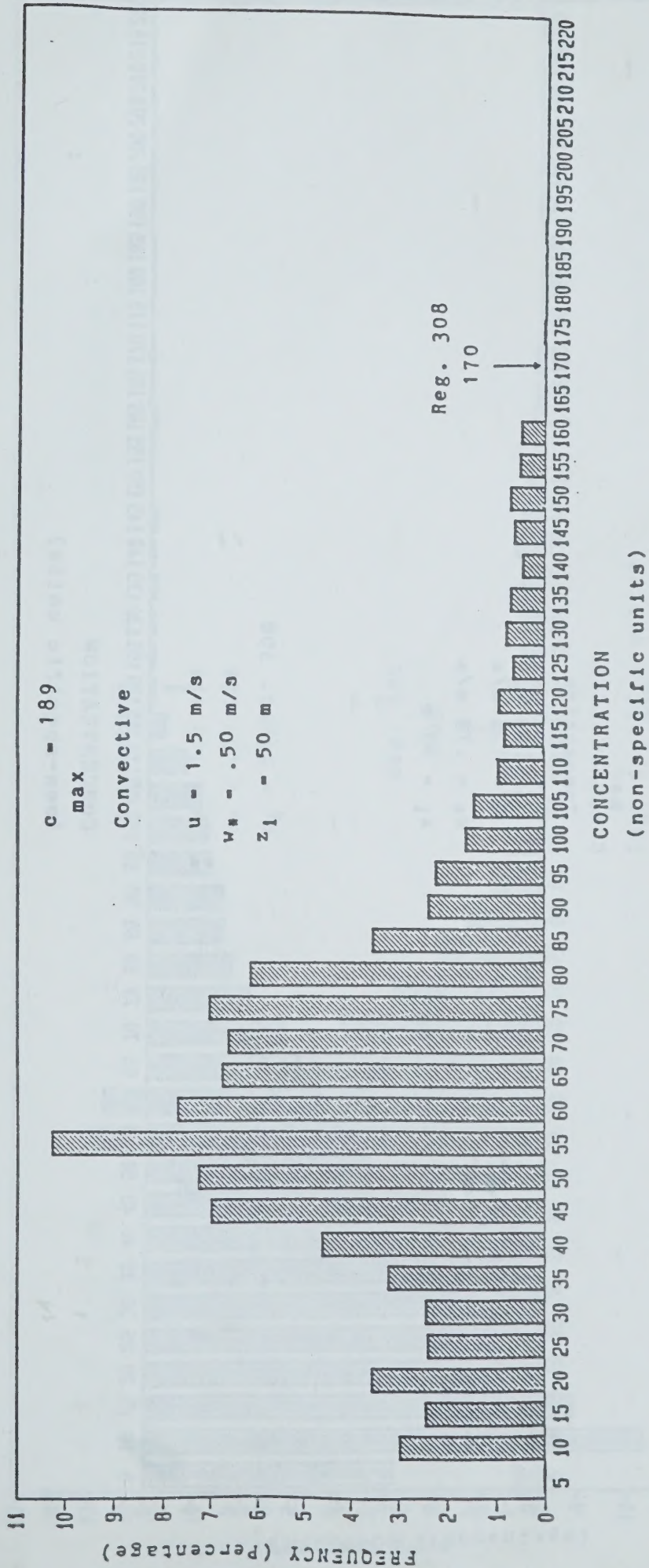


SELECTED SOURCES

Source	Height (z_g) metres	Diameter (d_g) metres	Velocity (w_g) m/s	Temperature (T_g) °C	Comments
1. Generic Municipal Incinerator (100 tonnes/day)	30	1.0	18.	90.	no nearby buildings
2. Generic Municipal Incinerator (500 tonnes/day)	70	2.3	18.	90.	no nearby buildings
3. Generic Sewage Sludge Incinerator (60 tonnes/day)	30	0.9	18.	35	no nearby buildings
4. A Very Tall Industrial Source	380	13.7	17.	140	no nearby buildings
5. A Large Industrial	190	9.1	4.	150	no nearby buildings

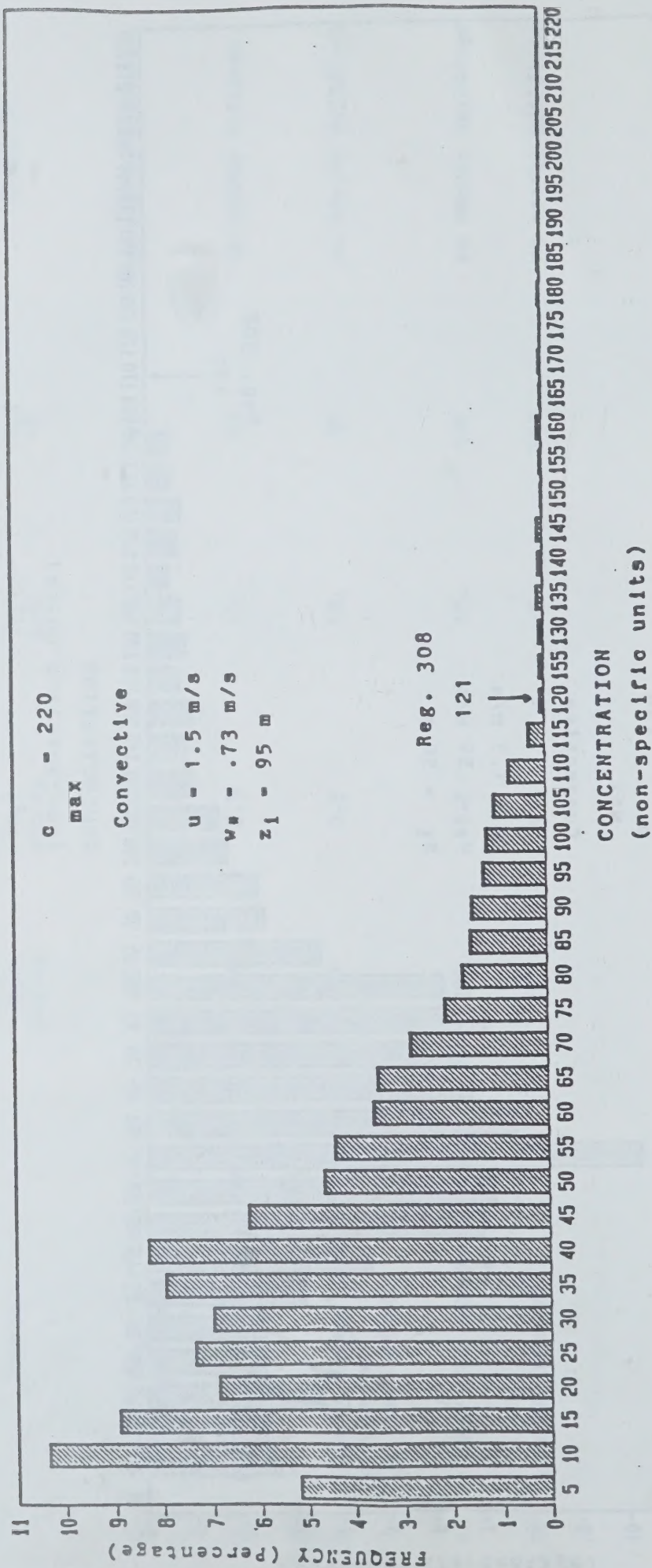
SOURCE #1

HOURLY AVERAGE CONCENTRATION



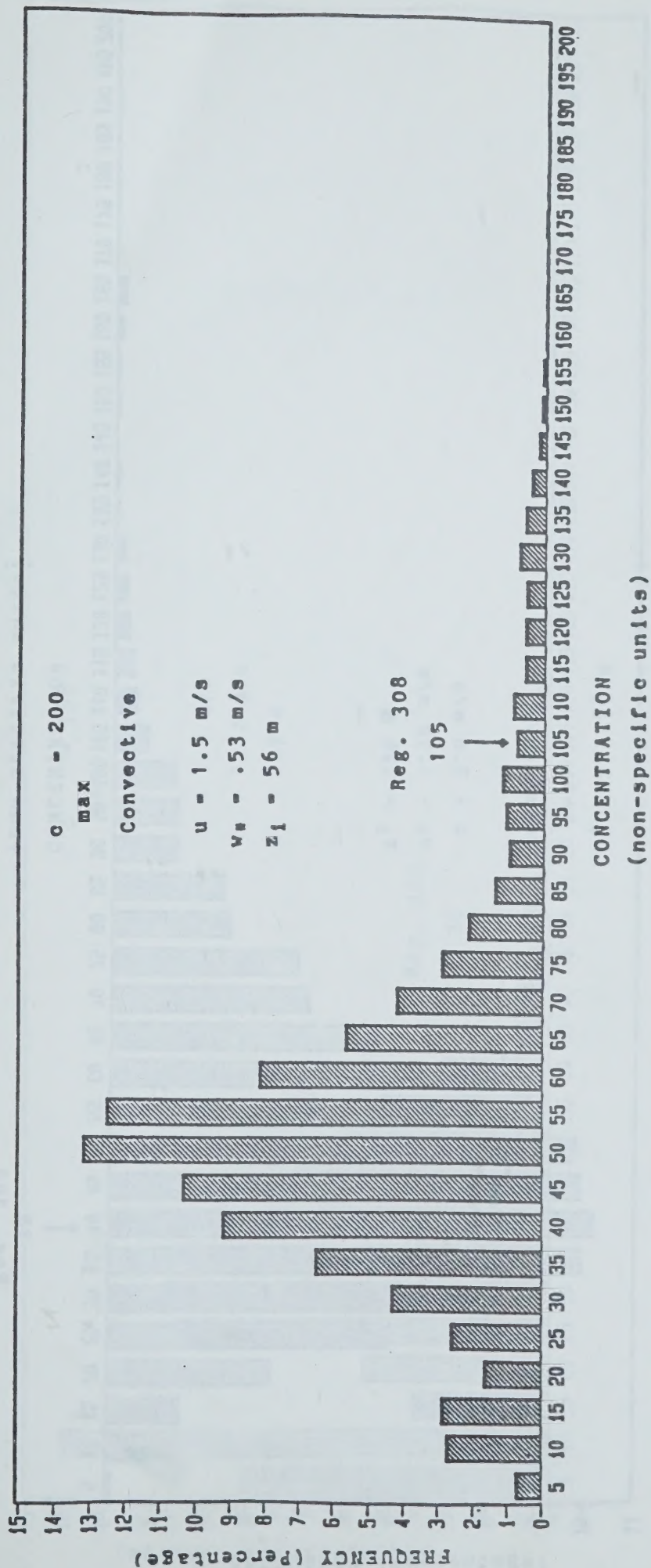
SOURCE #2

HOURLY AVERAGE CONCENTRATION



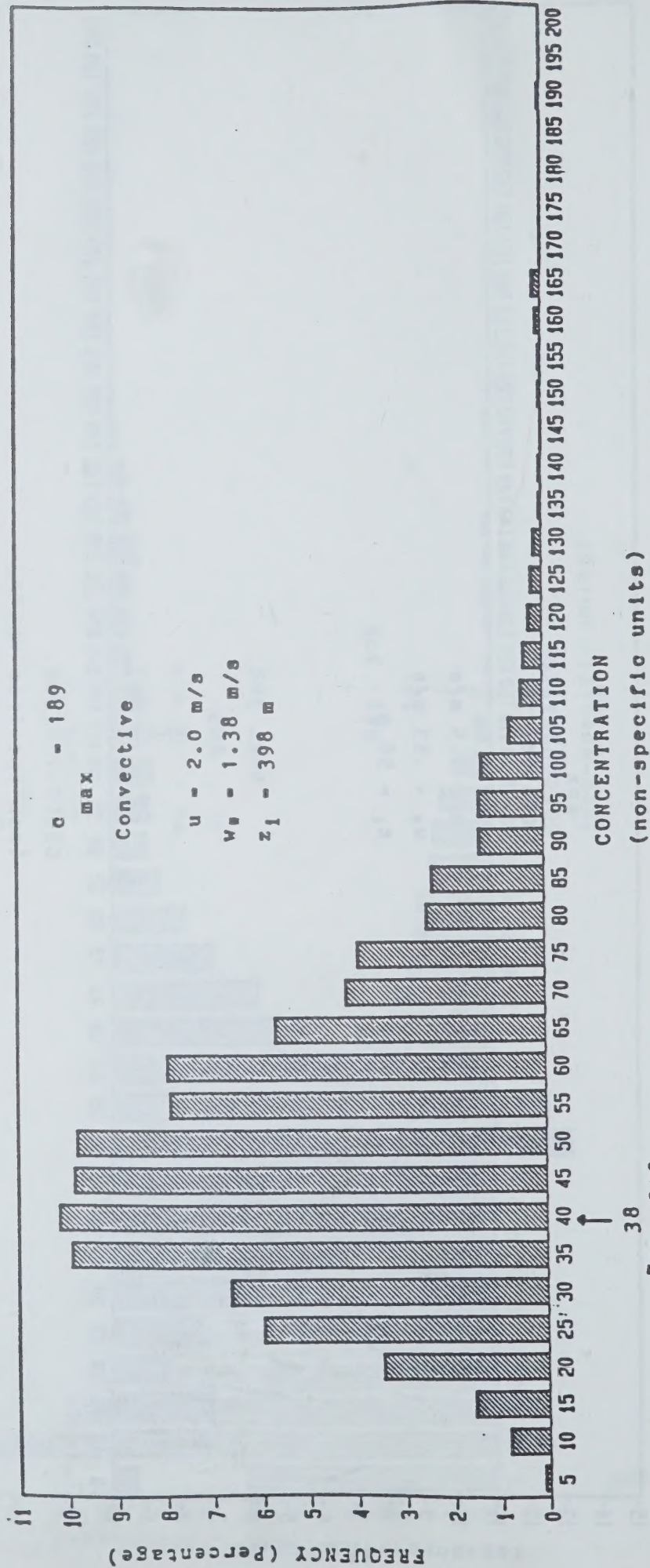
SOURCE #3

HOURLY AVERAGE CONCENTRATION



SOURCE #4

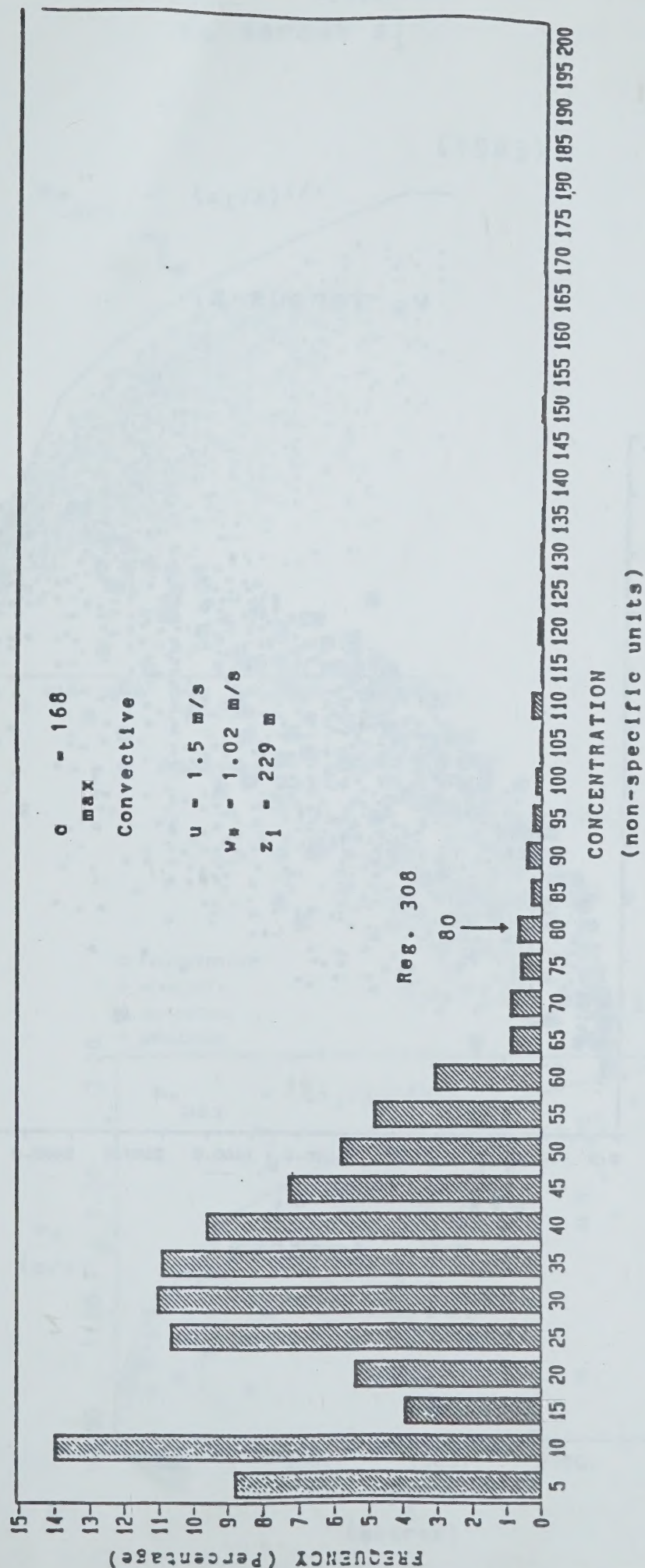
HOURLY AVERAGE CONCENTRATION



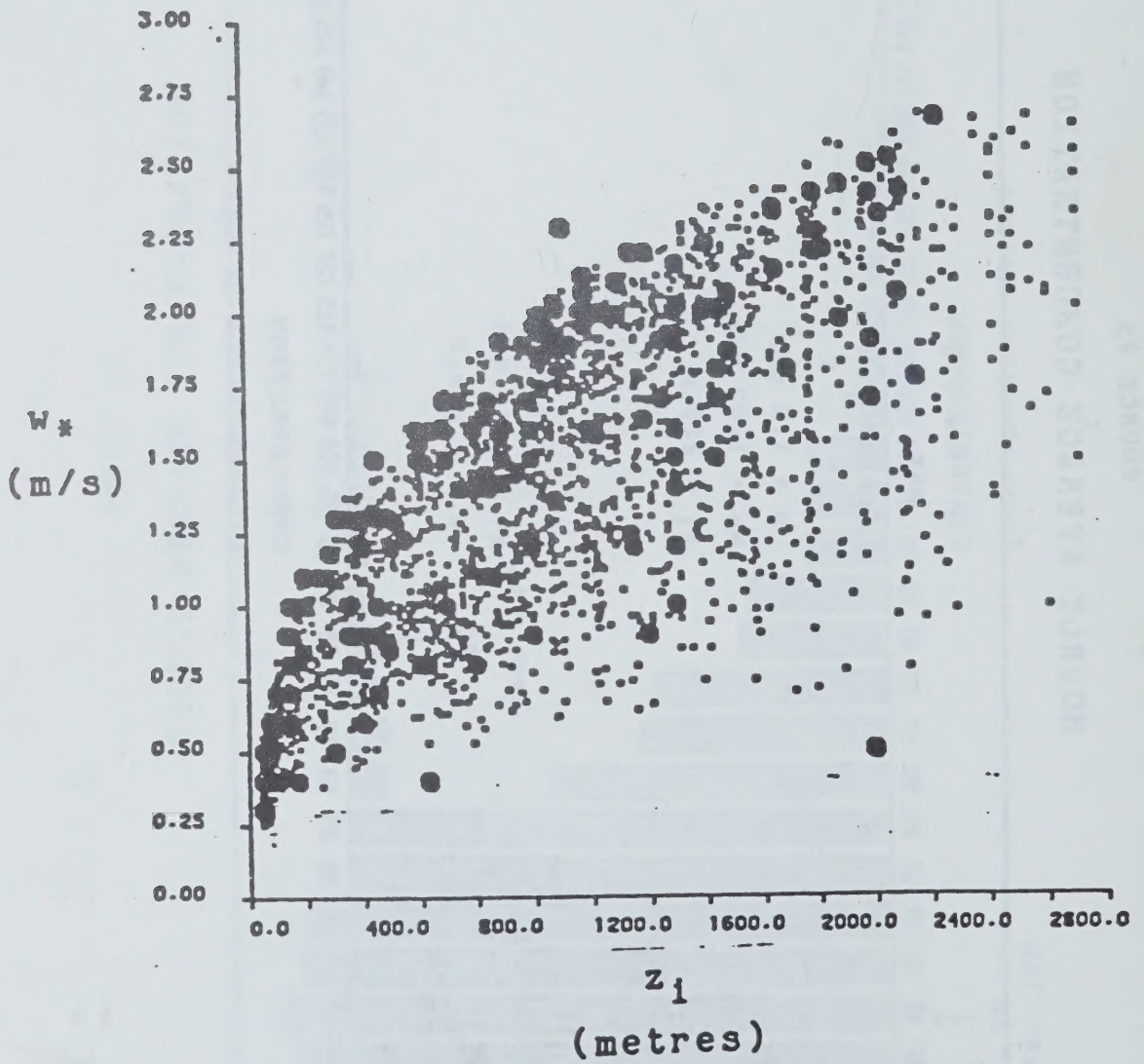
38
Reg. 308

SOURCE #5

HOURLY AVERAGE CONCENTRATION

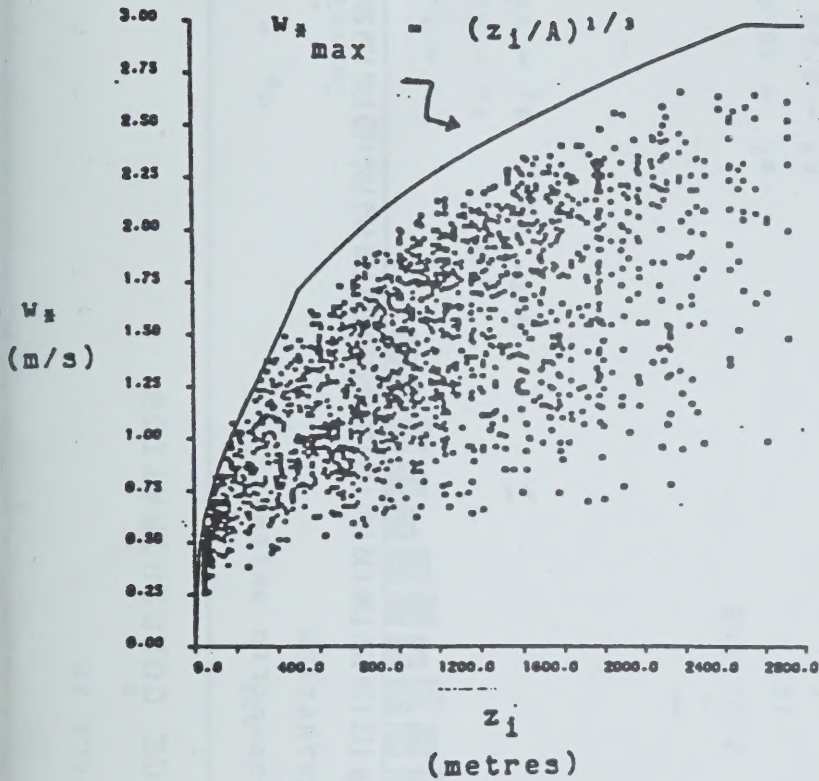


w_* versus z_1



w_* versus z_1

(1983)

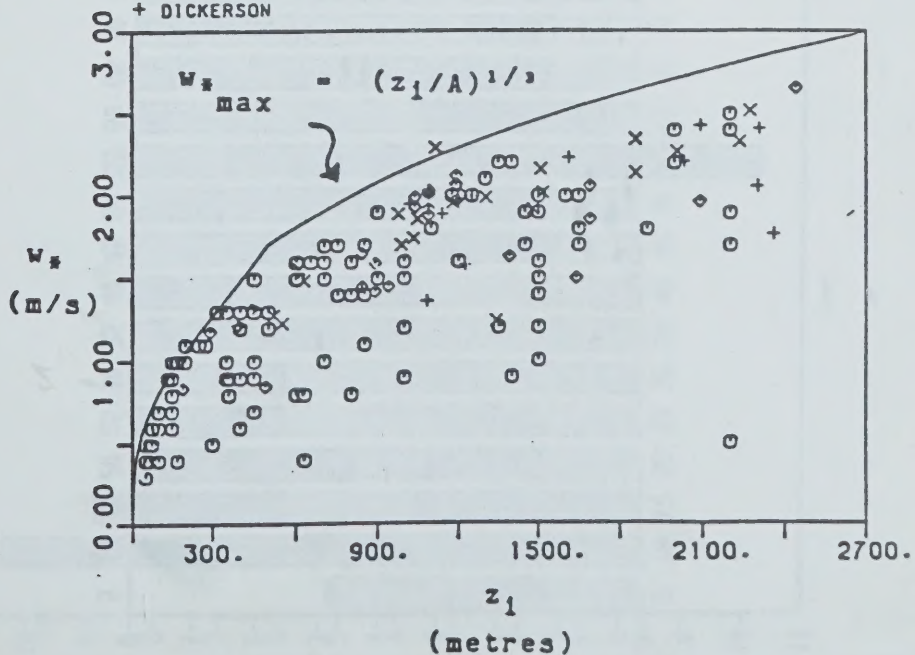


$$A = (500 - z_1)/4.5 + 100 \quad z_1 < 500 \text{ m}$$

$$A = 100 \quad z_1 > 500 \text{ m}$$

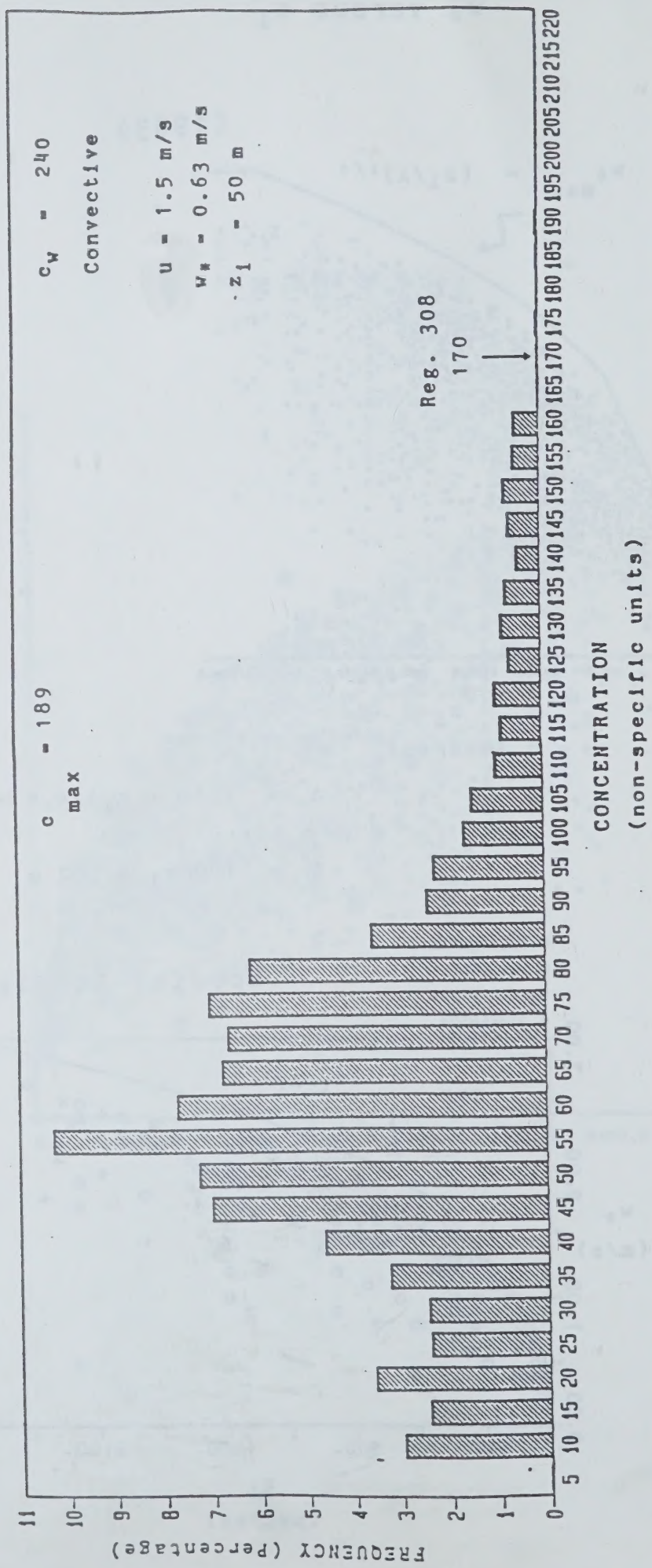
- FALCONBRIDGE
- ◇ MINNESOTA
- × MORGANTOWN
- + DICKERSON

Special Studies

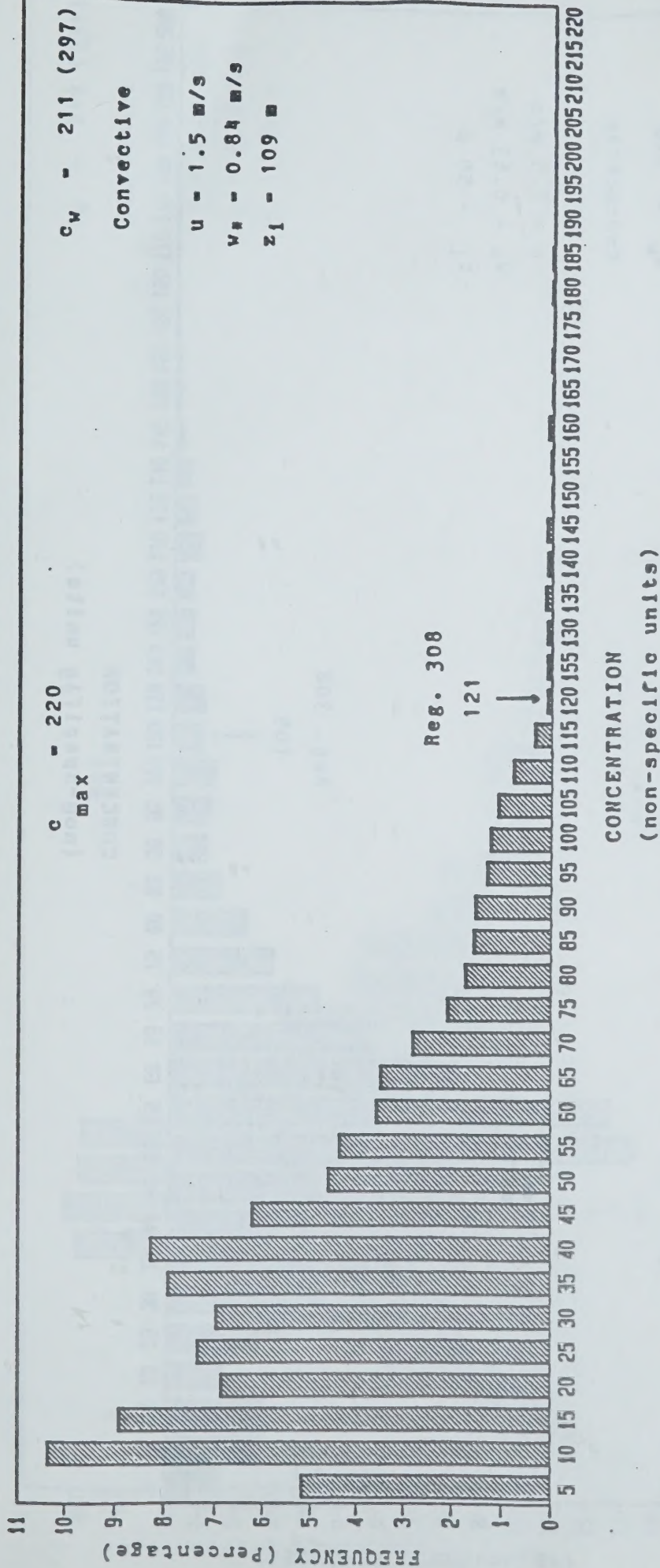


SOURCE #1

HOURLY AVERAGE CONCENTRATION

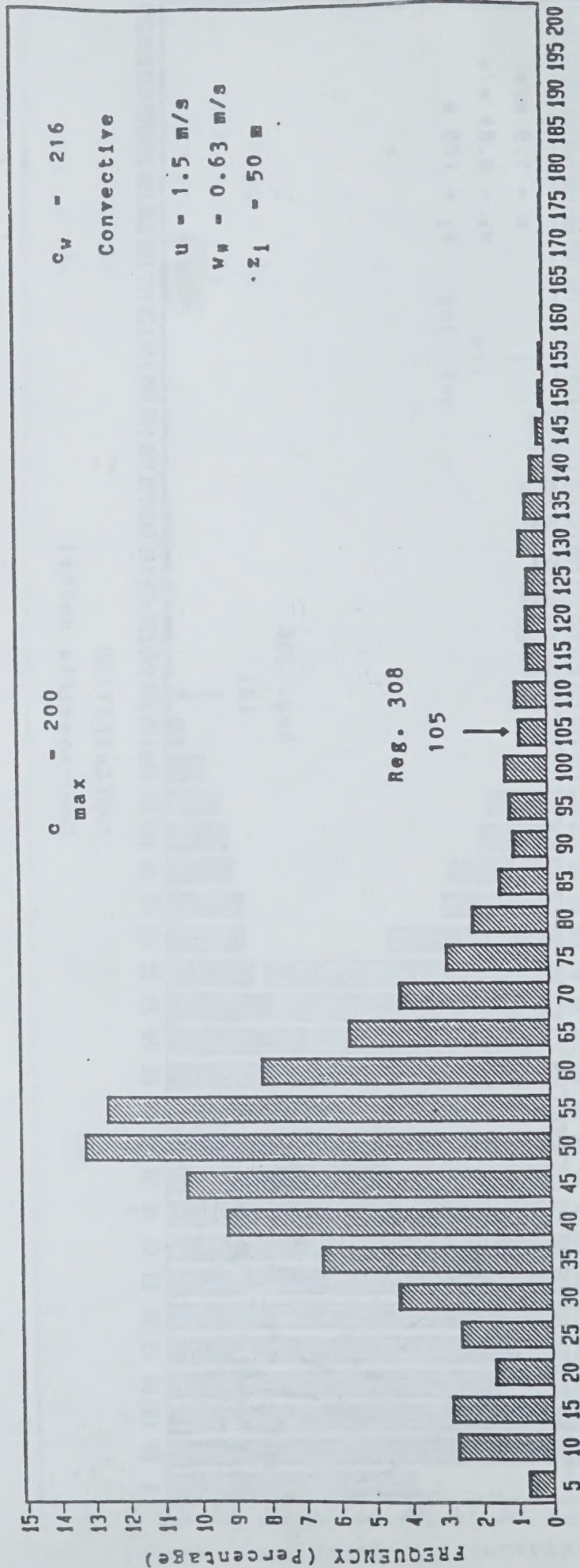


HOURLY AVERAGE CONCENTRATION



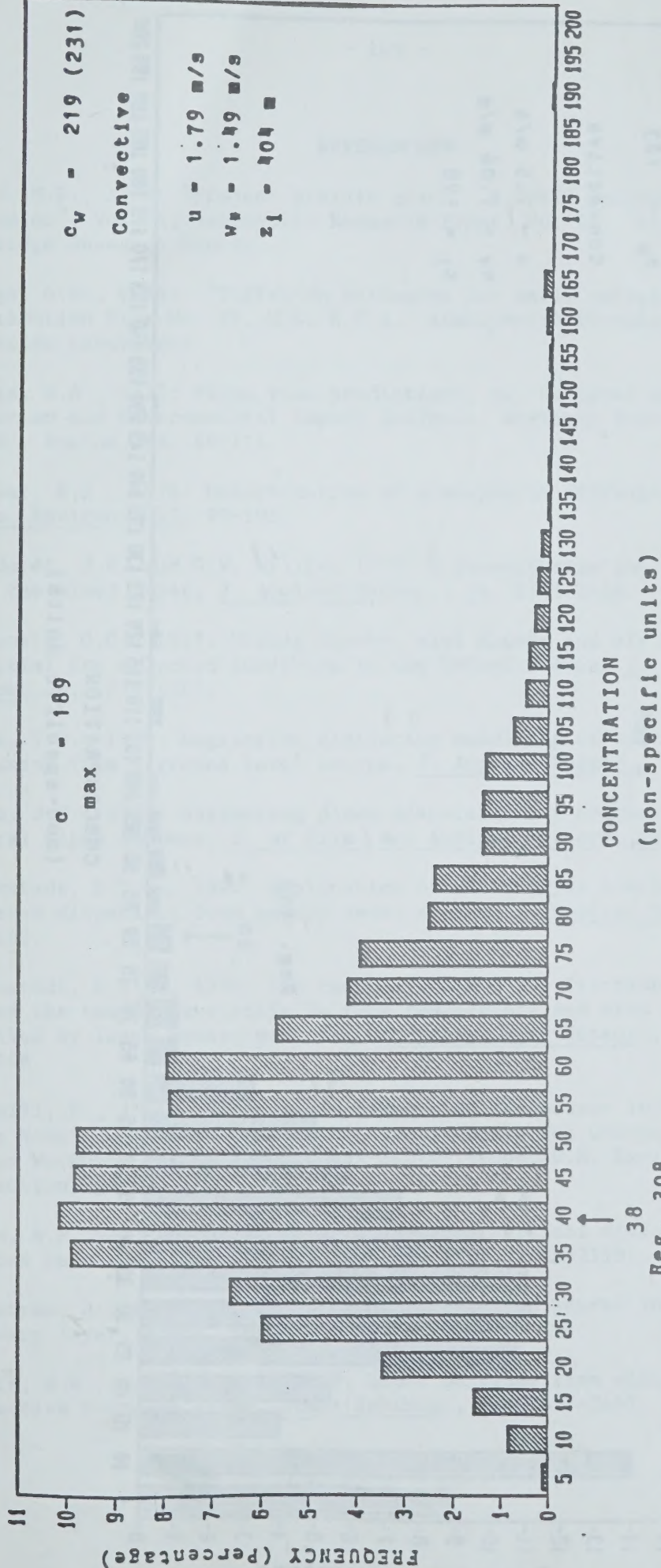
SOURCE #3

HOURLY AVERAGE CONCENTRATION



SOURCE #4

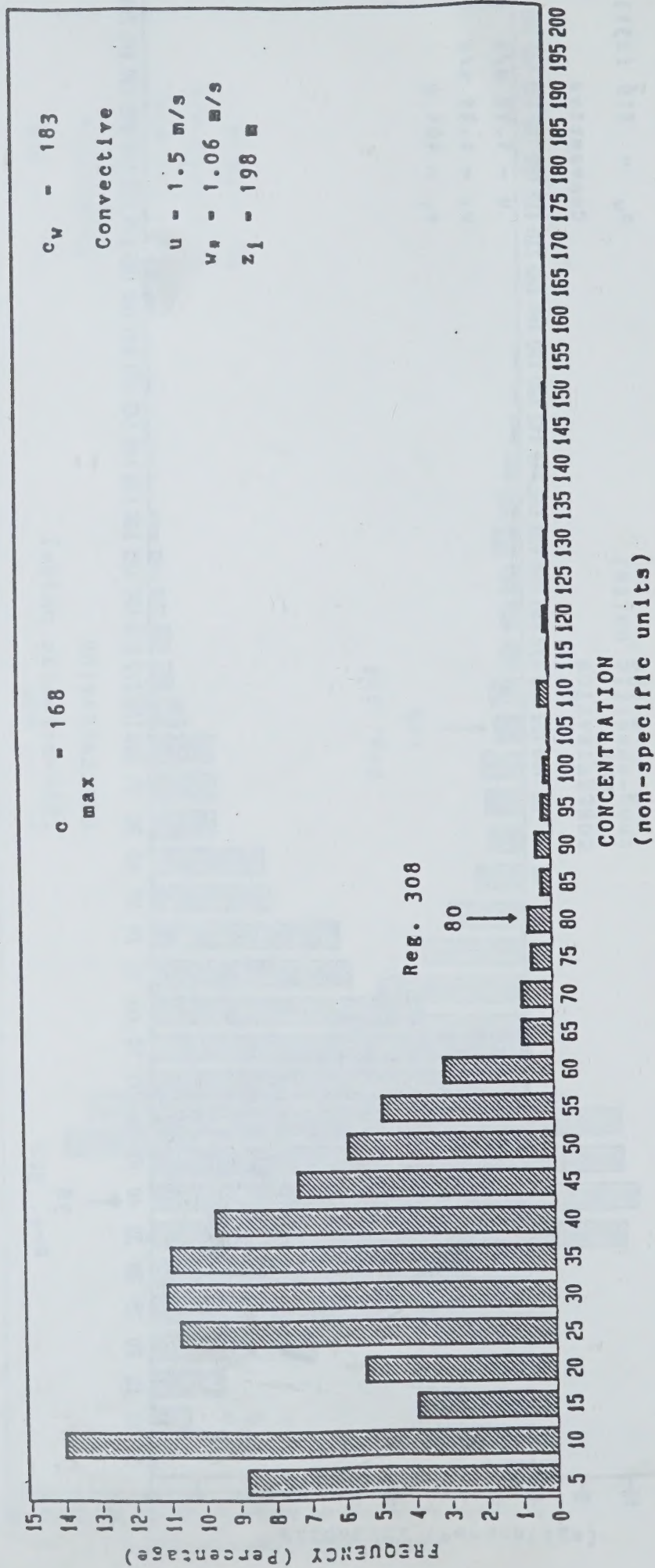
HOURLY AVERAGE CONCENTRATION



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Reg. 308

SOURCE #5

HOURLY AVERAGE CONCENTRATION



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- Willis, G.W., and J.W. Deardorff, 1983: On plume rise within the convective boundary layer, Atmos Environ., 17, 2435-2447.

**PLUME PENETRATION ABOVE THE
CONVECTIVE BOUNDARY LAYER**

**AN ACTION ITEM
FROM THE
REGULATION 308 REVIEW
MODELLING WORKSHOP
JUNE 25-26, 1986**

B. LEY

**ATMOSPHERIC MODEL DEVELOPMENT UNIT
AIR RESOURCES BRANCH
JULY, 1986**

PLUME PENETRATION ABOVE THE CONVECTIVE BOUNDARY LAYER

THE CURRENT PROPOSAL

Turbulence in the convective boundary layer is driven by heating of the surface. Vigorous vertical mixing develops with updrafts and downdrafts (convective eddies) extending through nearly the whole boundary layer. The convective boundary layer is capped by stable air; however, the top of the boundary layer undulates due to the impingement of strong updrafts and due to atmospheric waves associated with the capping inversion (Figure 1, p. 133). These fluctuations may entrain some of the stable air from aloft and mix it down into the boundary layer. There can be considerable wind shear near the top of the boundary layer.

In general, material released within the convective boundary layer will be rapidly mixed as the plume is essentially ripped apart as it is alternately caught in the updrafts and downdrafts. Material caught in downdrafts may mix quickly to the ground. This rapid convective mixing of material from elevated releases in the convective boundary layer has been observed both in field studies and in laboratory experiments. Unfortunately, the majority of these experiments are associated with plumes which have relatively low buoyancy (in a non-dimensional sense, $F^* < 0.1$) and which have release heights significantly less than the depth of the convective boundary layer ($z_s/z_i \leq 0.5$). Little quantitative information is available for very buoyant or very elevated releases (Briggs, 1985).

Based on a limited set of observations (Deardorff and Willis, 1984,; Willis and Deardorff, 1983; Willis and Hukari, 1984; Weil and Brower,

1982) it has been noted that very buoyant plumes can loft or impinge on the top convective layer with enough buoyancy to induce increased lateral spread and that the residual buoyancy can resist downward mixing by convective eddies until the buoyancy has been reduced by lateral spreading. (AMS/EPA Workshop on Updating Applied Diffusion Models, January 1984: Briggs, 1985). If the plume is extremely buoyant it can penetrate the capping inversion.

A review of available plume rise and plume penetration models determined that there are currently no models available for the convective boundary layer which meet our model selection criteria (i.e. that the model be scientifically credible and show good performance when evaluated with observations). Hence, in the Ministry's review of "Air Quality Models Suitable for Regulatory Applications" revised in June 1986, it was proposed that for all elevated releases within the convective boundary layer it be assumed there is no plume penetration above the capping inversion. This assumption will be conservative (in the sense that it will yield larger calculated concentrations) in those cases for which a source has a relatively large buoyancy and for a very large release height with respect to boundary layer height. This conservative approximation is proposed in the absence of tested models and is intended to be philosophically in keeping with definition of "worst-case" modelling, insomuch as the "worst-case" model of concentration will yield an upper bound estimate of the concentration due to a specified release.

ALTERNATIVE APPROACHES

As noted above, it has been observed that very buoyant, elevated releases can penetrate the capping inversion of the convective boundary layer. In the absence of a model which fully treats the important

aspects of the rise in the presence of convective eddies and of the subsequent plume penetration of the undulating cap, several simplified methods for estimating plume penetration have been proposed.

Briggs (1975) (see also Weil and Brower, 1984) and Manins (1979) have proposed models for partial penetration of an elevated inversion layer by buoyant plumes. In all cases it is assumed that the layer into which the plume is released is nearly adiabatic ($\partial\theta/\partial z \approx 0$). These models do not consider the importance of convective updrafts and downdrafts in inhibiting plume rise. Rather, it is assumed that the plume rise is limited only by the stable stratification of the layer above the boundary layer.

Briggs' (1975) criteria for bent-over plumes assume that the fraction of material remaining in the boundary layer, f , may be estimated in the following manner:

$$\begin{aligned} f &= 0 \text{ if } (z_i - z_s)/\Delta h_i \leq 0.5 \\ f &= 1 \text{ if } (z_i - z_s)/\Delta h_i \geq 1.5 \\ f &= (z_i - z_s)/\Delta h_i - 0.5 \text{ otherwise,} \end{aligned} \quad (1)$$

$$\text{where } \Delta h_i = 2.6 (F/uS)^{1/3}, \quad (2)$$

$$\text{and } S = \frac{g}{T_a} \frac{\partial\theta}{\partial z}. \quad (3)$$

Implicit in this calculation are the assumptions that the plume is rectangular in shape with a half width of $\frac{1}{2}\Delta h$ and that the stability, S , of the layer above z_i may be extended downward to the stack top for the purpose of approximating the plume rise, Δh .

To evaluate plume penetration using Briggs' formula, knowledge of the potential temperature gradient in the elevated stable layer is

required. Weil and Brower (1984) assumed a default value of $\partial\theta/\partial z = 0.01$ °C/m but do not provide data to support their choice. Based on climatological summaries of rawinsonde observations (see the Appendix attached), it is seen that the weighted mean value of $\partial\theta/\partial z$ for Flint, MI, is approximately 0.023 °C/m. The maximum potential temperature lapse rate has been observed to exceed 0.07 °C/m (Holzworth and Fisher, 1979). Figure 2 shows an example of a sharp temperature inversion for Flint, MI. In this case the elevated temperature inversion exceeds 11°C over a depth of 200 meters.

Manins (1979) studied buoyant plume penetration of a thin elevated inversion using a water tank. Manins notes that some material will penetrate a thin inversion layer if the plume buoyancy, when it reaches the top of boundary layer, exceeds the strength of the inversion.

Assuming a Gaussian plume distribution and using geometric arguments, Manins defines the fraction of the material trapped by the inversion as:

$$f = 0.08 P^{-1} - (P - 0.08) \quad (4)$$

where $P = F / (u b_i [z_i - z_s]^2) \quad (5)$

The inversion strength $b_i = (g/\theta_i) \Delta\theta_i$ can be calculated given the change in potential temperature, $\Delta\theta_i$, across the depth of the inversion. See Note 1 for a climatological estimate of $\Delta\theta_i$.

Briggs (1975) modelled plume penetration through a thin elevated inversion in a similar manner, but assumed that the plume had a rectangular vertical distribution. Briggs proposed that

$$f = \frac{2}{3} \left[1 + \frac{28F}{u b_i (z_i - z_s)^2} \right]^{\frac{1}{2}} - \frac{1}{2}$$

Comparison of Briggs' thin inversion formula (1975) and Manins' (1979) formulation indicates that Manins' proposal for estimating plume penetration is somewhat more conservative (i.e. yields less penetration for a given plume buoyancy). Neither models consider the importance of convective eddies on reducing the plume rise.

Kerman (1981) reviewed Manins' model and noted that Manins' plume penetration factor, P , (Eqn. 5) is determined by the relative ratio of buoyancies of the ambient retardation at the inversion and of the plume at the inversion. Kerman proposed that, rather than a discontinuous buoyancy reduction localized at the inversion, a plume released into a convective boundary layer would encounter deceleration distributed over a depth $(z_i - z_s)$. Kerman proposes that the characteristic retarding buoyancy in the convective boundary layer may be expressed as:

$$b \sim w_*^2 / (z_i - z_s) \quad (7)$$

Replacing b_i with b in Manins' calculation of plume penetration factor, P , yields an estimate of plume impingement on the capping inversion. Not included in this model is an estimate of the fraction of material which will penetrate the inversion following impingement.

Each of the plume penetration models described above omits specific aspects of the physical processes in the convective boundary layer which affect the impingement of a plume on the capping inversion, and the loss of material from the boundary layer. Briggs' (1975) and Manins' (1979) models ignore the influence of convective updrafts and downdrafts on the inhibition of plume rise in the boundary layer. Kerman's (1981) model considers only impingement of the plume on the inversion and, hence, cannot be used to estimate material penetrating above the inversion. It should be noted that material trapped in the inversion may be entrained by the stronger updrafts and mixed down into the boundary layer.

A major concern associated with Briggs' and Manins' models is that these simple formulations may not be conservative approximations to plume penetration (i.e. these model may overestimate plume penetration). Because these models have not been evaluated with data for convective conditions, neither model has been included in the Ministry's review of models suitable for regulatory applications. However, during the Modelling Workshop held June 25-26, 1986, concern was expressed regarding the omission of a calculation of plume penetration for very buoyant, elevated releases. To address this concern, the effect of Briggs' and Manins' plume penetration formulations on the calculated ground level concentration for five selected sources is presented in the next section. It must be stressed that these results intercompare models and in no manner evaluate these models.

COMPARISON OF MODEL CALCULATIONS WITH AND WITHOUT PENETRATION

Five sources were assessed using a year of hourly meteorological data. Table 1 summarizes the stack parameters for these sources. Hourly average ground level concentrations during convective periods were calculated for each of these sources' assuming no penetration of the plume above the capping inversion. These results are compared in this section with the hourly average ground level concentration calculated assuming Briggs' penetration formulation (Eqn. 1) with values of $\partial\theta/\partial z$ based on climatological data and calculated assuming Manins' penetration formulation (Eqn. 4) with a climatological value of $\Delta\theta$.

Tables 2 through 6 summarize the results of the intercomparison of plume penetration models for sources 1 through 5 respectively. The results for the model concentration calculations without plume penetration are summarized in the first column of these tables.

Columns 2 through 4 summarize the results of the concentration calculation with Briggs' plume penetration formulation (Eqn. 1) for three values of the potential temperature lapse rate in the capping inversion (isothermal, the climate average and the climate maximum, respectively). Columns 5 and 6 summarize the results of the concentration calculation with Manins' plume penetration formulation (Eqn. 4) for two values of the potential temperature difference across the inversion ($\Delta\theta = 5^{\circ}\text{C}$ and $\Delta\theta = 10^{\circ}\text{C}$ from the Appendix, respectively). A brief summary of the results follows.

Source 1: This source represents a medium sized, generic municipal incinerator with a release height of 30 m and moderate buoyancy. Briggs' plume penetration model for the values of $\partial\theta/\partial z$ studied reduces the modelled maximum concentration during convective period by 15% from 189 units to 161 units. Without the plume penetration model the calculated maximum hourly average maximum concentration exceeded 161 units for nine hours of the year modelled. Manins' plume penetration model estimates that if the convective boundary layer is capped by a layer with $\Delta\theta = 5^{\circ}\text{C}$, the maximum annual hourly average concentration is 185 units (2% less than the maximum concentration if no penetration is allowed). Without penetration the maximum hourly average concentration exceeds the 185 units for three hours during the model year. If the capping layer has $\Delta\theta = 10^{\circ}\text{C}$, Manins' model predicts that emissions from this source will not be sufficiently buoyant to penetrate above the inversion.

Source 2: This source represents a large, generic municipal incinerator with a release height of 70 m and moderate buoyancy. Including Briggs' plume penetration formulation in calculation of ground level concentration during convective periods yields a 45% reduction in the modelled annual maximum hourly average concentration when the potential temperature lapse rate is 0.01°C/m . It yields a

reduction of 36% when $\partial\theta/\partial z = 0.023$ °C/m and a reduction of 25% when $\partial\theta/\partial z = 0.07$ °C/m. Without plume penetration the calculated maximum concentration exceeded the maximum concentration calculated with plume penetration on 41, 24 and 9 hours during the model year for $\partial\theta/\partial z = 0.01, 0.023$ and 0.07 °C/m, respectively.

Manins' model for plume penetration of an inversion estimates a 20% reduction in the modelled annual maximum hourly average concentration when $\Delta\theta = 5^\circ\text{C}$, and a 19% reduction when $\Delta\theta = 10^\circ\text{C}$. For these cases the calculated concentration, assuming no penetration, exceeded the concentration calculated with plume penetration for 7 and 6 hours of the modelling year, respectively.

Source 3: This source represents a generic sewage incinerator with a 30 m release height and a low buoyancy release. Briggs' plume penetration model for values of $\partial\theta/\partial z$ studied reduces the calculated maximum concentration by 13%. During five hours of the model year the concentration calculated without allowing plume penetration exceeds the maximum concentration calculated using Briggs' model.

Manins' model predicts that this source would not have sufficient buoyancy to penetrate above inversions with $\Delta\theta = 5^\circ\text{C}$ or $\Delta\theta = 10^\circ\text{C}$.

Source 4: The source represents a very tall industrial stack similar to the largest industrial source in Ontario. Briggs' model for plume penetration estimates that the annual maximum hourly average concentration will be reduced by 43%, 35% or 30% for $\partial\theta/\partial z = 0.01, 0.023$ or 0.07 °C/m, respectively, from the concentration calculated without allowing plume penetration. For the values of the potential temperature gradient $0.01, 0.023$ and 0.07 °C/m the concentration

calculated without allowing plume penetration exceeded the maximum concentration calculated using Briggs' formulation for 28, 16 and 9 hours, respectively, during the model year.

Applying Manins' model to estimate plume penetration for this very buoyant source yields a reduction in the calculated annual maximum hourly average concentration of 30% and 24% for $\Delta\theta = 5^{\circ}\text{C}$ and 10°C , respectively. The calculated maximum concentration without penetration exceeds the annual maximum concentration with penetration for nine hours if $\Delta\theta = 5^{\circ}\text{C}$ and for eight hours if $\Delta\theta = 10^{\circ}\text{C}$.

Source 5: This source represents a large industrial chimney with moderately large initial buoyancy of the efflux. Briggs' plume penetration model estimates that the maximum annual hourly average concentration calculated with penetration will be 44%, 35% or 27% less than the concentration calculated without penetration, when the potential temperature lapse rate in the capping stable layer is 0.01°C , 0.023°C and 0.07°C , respectively. For these values of $\partial\theta/\partial z$, it is calculated that the maximum hourly average concentration without penetration exceeds the annual maximum with penetration for 38, 16 and 9 hours, respectively, during the model year.

Using Manins' model to estimate the reduction in ground level average concentration due to plume penetration of the capping inversion it was calculated that the annual maximum concentration would be reduced by 11% if plume penetration is modelled in this manner (for $\Delta\theta = 5^{\circ}\text{C}$ and $\Delta\theta 10^{\circ}\text{C}$). In these cases the calculated hourly maximum concentration determined without penetration exceeds the annual maximum calculated with penetration during two hours of the modelling year.

Figures 3 through 7 present frequency histograms of modelled concentration for sources #1 through #5, respectively. On each figure

there are six histograms, labelled i through vi, corresponding to the various calculations of plume penetration: Histogram i shows the annual frequency distribution of the maximum hourly average ground level concentration calculated assuming no material escapes from the convective boundary layer. Histograms ii, iii and iv present the annual frequency distribution of the maximum concentration determined using Briggs' (1975) model with $\partial\theta/\partial z = 0.01$ °C/m, 0.023 °C/m and 0.07 °C/m, respectively. Histograms v and vi present the frequency distribution of concentration calculated using Manins' (1979) model with $\Delta\theta = 5^\circ\text{C}$ and 10°C , respectively.

In all cases, the application of these simplified plume penetration formulations to the calculation of maximum hourly average concentration principally influences only the righthand tail of the frequency distribution. This change in the distribution of maximum concentrations is most evident for the taller sources with larger release buoyancies.

RECOMMENDATIONS

A primary goal of air quality modelling is to determine if the air quality objective (criteria) will be met. To meet this goal it is necessary that the models employed be evaluated with observational data to establish their skill in predicting air quality. Once the model has been tested the evaluation results may be employed to estimate the probability that the modelled concentration may be exceeded by the observed concentration. Hence, the model may be used to define the source constraints (e.g. emissions, stack parameters) with some degree of confidence.

Neither Briggs' (1975) nor Manins' (1979) plume penetration models have been evaluated for convective conditions. In addition, these models

require information regarding the potential temperature change across the inversion which is not routinely available on an hourly basis. Therefore, although they may be used to calculate air quality, they cannot be employed to estimate the probability that the observed concentration may exceed the modelled concentration. Hence, it is not possible to determine with some degree of confidence that a specified emission and source configuration will or will not meet the air quality objective.

The intercomparison of simple plume penetration models presented in the previous section suggests that for relatively short stacks, and for releases with only moderate initial buoyancy, the assumption of no plume penetration above the inversion for releases into a convective boundary layer yields calculated concentrations not significantly different from the concentration calculated using plume penetration models of Briggs and Manins. For tall and buoyant sources, the results of the plume penetration models are somewhat different from results of the model assuming no penetration. Because the plume penetration models have not been evaluated, the significance of the calculated concentration reductions cannot be assessed.

Therefore, it is recommended that the concentration calculation for releases into the convective boundary layer not include a plume penetration formulation until a scientifically credible, evaluated plume penetration model is available. When a suitable model becomes available it should be incorporated into the model package.

Choosing to employ one of the currently available simple models of plume penetration would increase the probability that the modelled concentration would be exceeded by the observed concentration. However, both Briggs' and Manins' models suggest that plume penetration will reduce the hourly maximum concentration to less than the annual

hourly maximum calculated without penetration for only a few hours during the model year. Hence, for a given source configuration, there would be a very limited number of periods during the year when the probability of exceeding the air quality objectives would be somewhat greater. Only evaluation of the models can determine the magnitude of the increased probability.

Including a simple formulation of plume penetration under convective conditions is not recommended without an evaluation of the model, as the probability of the observed concentration exceeding the modelled concentration cannot be assessed. Hence, when superseded by a scientifically credible, evaluated plume penetration model, previously determined emission limits may not be acceptable.

NOTE 1

CLIMATOLOGICAL INVERSION DATA
BASED ON STATISTICAL SUMMARIES
OF RAWINSONDE OBSERVATION

Holzworth and Fisher (1979) have compiled statistical summaries of vertical temperature profiles based on five years of data collected at rawinsonde stations across the United States. Routinely, rawinsondes are released twice daily to provide snap-shots of the vertical profiles of temperature, pressure, humidity and winds. In general, the release times are 1115 GMT and 2315 for the 1200 GMT (700 EST) and 000 GMT (1900 EST) profiles respectively. For the purposes of our study the statistical data for Flint, MI, will be used, as this station was previously selected for the development of our modelling dataset.

Based on the figures in the report by Holzworth and Fisher (1979), the following statistics for Flint, MI, have been derived:

1. Based on the early morning sounding (1115 GMT) annually, temperature inversions are observed to occur on approximately 91.5% of the days. (Holzworth and Fisher, (1979) Figures 16-19).
2. On average during a year at the 1115 GMT sounding, 54.8% of the days have temperature inversions which extend upward from the surface, while on approximate 36.8% of the days elevated temperature inversions are observed. (Holzworth and Fisher, (1979) Figures 16-19).

3. Holzworth and Fisher report positive vertical temperature gradients, $\Delta T/\Delta H$, according to the frequency of occurrence of various ranges. Assuming each range may be represented by its mid-point (except the maximum range which was assigned its lower bound), the weighted average temperature gradient for a surface based inversion for the 1115 GMT sounding is $\Delta T/\Delta H = 0.019$ °C/m. (Holzworth and Fisher (1979), Figures 50-53).
4. Based on the same assumptions as noted in point 3, the weighted average temperature gradient for an elevated inversion for the 1115 GMT sounding is $\Delta T/\Delta H = 0.010$ °C/m. (Holzworth and Fisher (1979), Figure 55).
5. Assuming that the temperature gradient is adiabatic during periods when no inversion is observed (i.e. $\Delta T/\Delta H = -0.010$ °C/m), and using the statistics from points 1-4, yields a calculated weighted annual average 1115 GMT inversion temperature gradient of $\Delta T/\Delta H = 0.013$ °C/m or, alternatively, a potential temperature gradient $\Delta \theta/\Delta H = 0.023$ °C/m.
6. The maximum range for $\Delta T/\Delta H$ reported by Holzworth and Fisher is $\Delta T/\Delta H > 6.0$ °C/100 meters. Surface based inversions of this magnitude are reported as approximately 2% for the soundings. Hence, it is proposed that $\Delta T/\Delta H = 0.060$ °C/m or $\Delta \theta/\Delta H = 0.070$ °C/m represent an estimate of maximum inversion strength.
7. Holzworth and Fisher report the thickness of elevated inversions according to the frequency of occurrence of various ranges. Assuming each range may be represented by its midpoint (except the maximum range which is assigned its lower bound), the weighted average inversion depth, ΔH , for elevated inversions based on the 1115 GMT sounding is 467 m. (Holzworth and Fisher (1979), Figures 42-45).

For the 2315 GMT sounding the weighted average inversion depth is 420 m. (Holzworth and Fisher (1979), Figures 46-49).

The weighted average for both soundings is 439 m.

8. The mean potential temperature gradient across an inversion is estimated from points 5 and 7 above as $\Delta\theta = 10^{\circ}\text{C}$ ($0.023^{\circ}\text{C/m} \times 439 \text{ m}$). This calculation assumes that the inversion depth and the temperature gradient are independent of each other. This is not strictly true; however, Holzworth and Fisher do not report $\Delta\theta$ statistics.

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TABLE 1

SELECTED SOURCES

Source	Height (z_g) (metres)	Diameter (d_g) (metres)	Velocity (w_g) m/s	Temperature (T_g) °C	Comments
1. Generic Municipal Incinerator (100 tonnes/day)	30	1.0	18.	90	no nearby buildings
2. Generic Municipal Incinerator (500 tonnes/day)	70	2.3	18.	90.	no nearby buildings
3. Generic Sewage Sludge Incinerator (60 tonnes/day)	30	0.9	18.	35	no nearby buildings
4. A Very Tall Industrial Source	380	13.7	17.	140	no nearby buildings
5. A Large Industrial	190	9.1	4.	150	no nearby buildings

TABLE 2
SOURCE #1

MAXIMUM HOURLY AVERAGE CONCENTRATION
CALCULATED USING VARIOUS PLUME PENETRATION ESTIMATES

	No Penetration	Briggs Model $\partial\theta/\partial z = 0.01^\circ/\text{m}$ (isothermal cap)	Briggs Model $\partial\theta/\partial z = 0.02^\circ/\text{m}$ (climate average)	Briggs Model $\partial\theta/\partial z = 0.07^\circ/\text{m}$ (climate maximum)	Manins Model $\Delta\theta = 5^\circ\text{C}$	Manins Model $\Delta\theta = 10^\circ\text{C}$
Maximum Hourly Average Concen- tration C_{max}	189	161	161	161	185	189
% Difference between C_{max} without pene- tration and C_{max} with penetration	-	-15%	-15%	-15%	-2%	0%
z_1 for C_{max} w for C_{max} u for C_{max}	50 m 0.50 m/s 1.5 m/s	1673 m 2.20 m/s 2.6 m/s	1673 m 2.20 m/s 2.6 m/s	1673 m 2.20 m/s 2.6 m/s	56 m 0.53 m/s 1.5 m/s	50 m 0.50 m/s 1.5 m/s
% Convective cases with plume pene- tration (excluding $z_s > z_1$)	0%	6.3%	5.3%	4.2%	2.0%	0%
# hours when C without penetration exceeds C_{max} with pene- tration	-	9	9	9	3	0

TABLE 3

SOURCE #2

MAXIMUM HOURLY AVERAGE CONCENTRATION
CALCULATED USING VARIOUS PLUME PENETRATION ESTIMATES

	No Penetration	Briggs Model $\partial\theta/\partial z = 0.01^\circ/\text{m}$ (isothermal cap)	Briggs Model $\partial\theta/\partial z = 0.02^\circ/\text{m}$ (climate average)	Briggs Model $\partial\theta/\partial z = 0.07^\circ/\text{m}$ (climate maximum)	Manins Model $\Delta\theta = 5^\circ\text{C}$	Manins Model $\Delta\theta = 10^\circ\text{C}$
Maximum Hourly Average Concen- tration C_{max}	220	121	141	165	176	178
% Difference between C_{max} without pene- tration and C_{max} with penetration	-	-45%	-36%	-25%	-20%	-19%
z_1 for C_{max} w for C_{max} u for C_{max}	95 m 0.73 m/s 1.5 m/s	324 m 1.28 m/s 1.5 m/s	190 m 1.07 m/s 2.0 m/s	170 m 0.97 m/s 1.5 m/s	105 m 0.81 2.5 m/s	105 m 0.81 2.5 m/s
% Convective cases with plume pene- tration (excluding $z_g > z_1$)	0%	6.7%	5.7%	3.9%	1.9%	1.6%
# hours when C without penetration exceeds C_{max} with pene- tration	-	41	24	9	7	6

TABLE 4
SOURCE #3

MAXIMUM HOURLY AVERAGE CONCENTRATION
CALCULATED USING VARIOUS PLUME PENETRATION ESTIMATES

	No Penetration	Briggs Model $\partial\theta/\partial z = 0.01^\circ/\text{m}$ (isothermal cap)	Briggs Model $\partial\theta/\partial z = 0.02^\circ/\text{m}$ (climate average)	Briggs Model $\partial\theta/\partial z = 0.07^\circ/\text{m}$ (climate maximum)	Manins Model $\Delta\theta = 5^\circ\text{C}$	Manins Model $\Delta\theta = 10^\circ\text{C}$
Maximum Hourly Average Concen- tration C_{max}	200	174	174	174	200	200
% Difference between C_{max} without pene- tration and C_{max} with penetration	-	-13%	-13%	-13%	0%	0%
z_1 for C_{max} w for C_{max} u for C_{max}	56 m 0.53 m/s 1.5 m/s	324 m 1.28 m/s 1.5 m/s	324 m 1.28 m/s 1.5 m/s	324 m 1.28 m/s 1.5 m/s	56 0.53 m/s 1.5 m/s	56 0.53 m/s 1.5 m/s
% Convective cases with plume pene- tration (excluding $z_s > z_1$)	0%	4.8%	4.1%	3.4%	0%	0%
# hours when C without penetration exceeds C_{max} with pene- tration	-	5	5	5	0	0

TABLE 5
SOURCE #4

MAXIMUM HOURLY AVERAGE CONCENTRATION
CALCULATED USING VARIOUS PLUME PENETRATION ESTIMATES

	Briggs Model $\partial\theta/\partial z = 0.01^\circ/\text{m}$ (isothermal cap)	Briggs Model $\partial\theta/\partial z = 0.02^\circ/\text{m}$ (climate average)	Briggs Model $\partial\theta/\partial z = 0.07^\circ/\text{m}$ (climate maximum)	Manins Model $\Delta\theta = 5^\circ\text{C}$	Manins Model $\Delta\theta = 10^\circ\text{C}$
No Penetration	189	107	123	133	143
Maximum Hourly Average Concen- tration C_{max}					
% Difference between C_{max} without pene- tration and C_{max} with penetration	-	-43%	-35%	-30%	-24%
z_1 for C_{max} w for C_{max} u for C_{max}	398 m 1.38 m/s 2.0 m/s	909 m 1.89 m/s 2.3 m/s	801 m 1.84 m/s 2.5 m/s	689 m 1.63 m/s 2.0 m/s	569 m 1.61 m/s 2.0 m/s
% Convective cases with plume pene- tration (excluding $z_g > z_1$)	0%	26.8%	21.1%	13.2%	11.7%
# hours when C without penetration exceeds C_{max} with pene- tration	-	38	16	9	8

TABLE 6

SOURCE #5

MAXIMUM HOURLY AVERAGE CONCENTRATION
CALCULATED USING VARIOUS PLUME PENETRATION ESTIMATES

	No Penetration	Briggs Model $\partial\theta/\partial z = 0.01^\circ/\text{m}$ (isothermal cap)	Briggs Model $\partial\theta/\partial z = 0.02^\circ/\text{m}$ (climate average)	Briggs Model $\partial\theta/\partial z = 0.07^\circ/\text{m}$ (climate maximum)	Manins Model $\Delta\theta = 5^\circ\text{C}$	Manins Model $\Delta\theta = 10^\circ\text{C}$
Maximum Hourly Average Concen- tration C_{max}	168	94	109	122	149	149
% Difference between C_{max} without pene- tration and C_{max} with penetration	-	-44%	-35%	-27%	-11%	-11%
z_1 for C_{max} w^* for C_{max} u for C_{max}	229 m 1.02 m/s 1.5 m/s	506 m 1.40 m/s 1.7 m/s	398 m 1.38 m/s 2.0 m/s	353 m 1.32 m/s 2.0 m/s	324 m 1.28 m/s 1.5 m/s	324 m 1.28 m/s 1.5 m/s
% Convective cases with plume pene- tration (excluding $z_s > z_1$)	0%	9.0%	6.7%	4.3%	2.8%	1.7%
# hours when C without penetration exceeds C_{max} with pene- tration	-	27	16	7	2	2

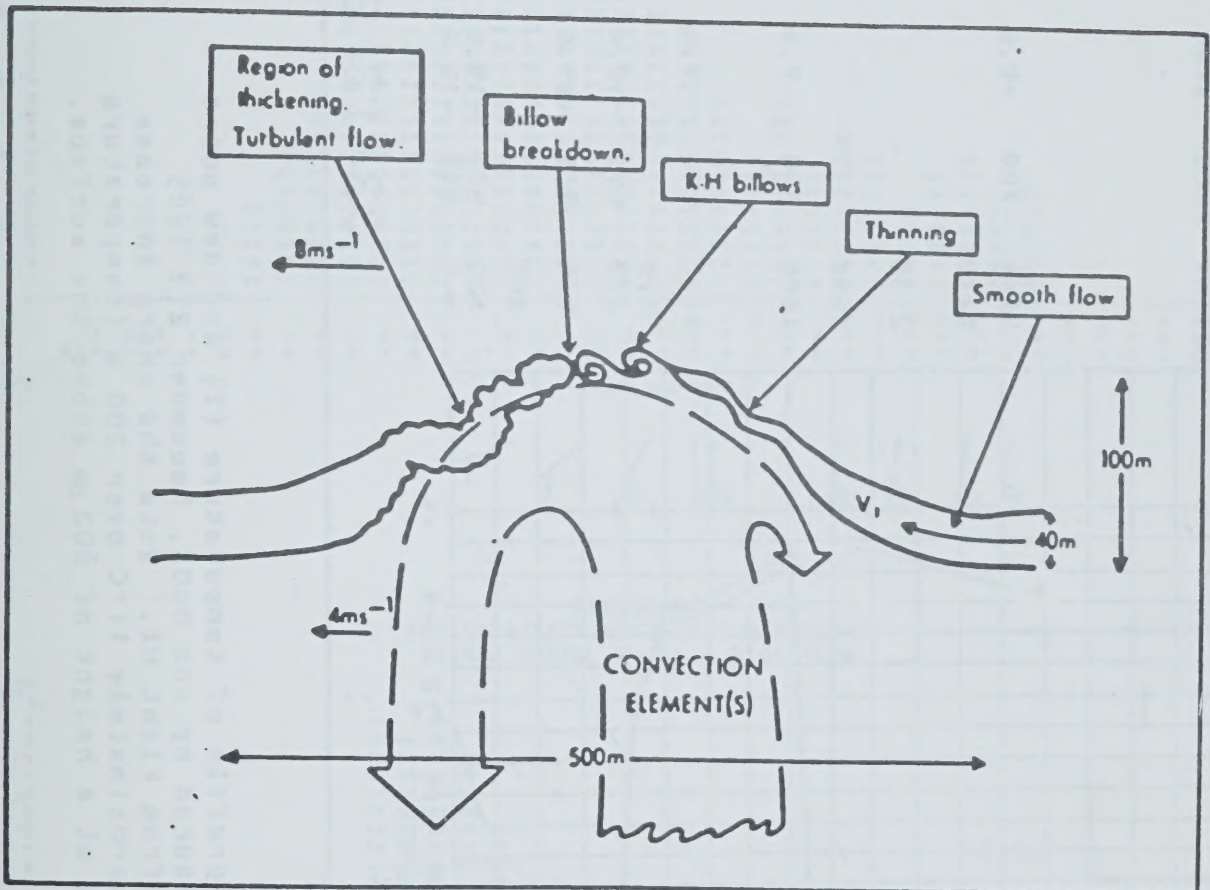


Figure 1: Schematic illustration of undulations including Kelvin-Helmholtz (K-H) waves on the inversion capping the convective boundary layer (after Rayment and Readings, Q.J.R. Meteor. Soc., 100, 221-223).

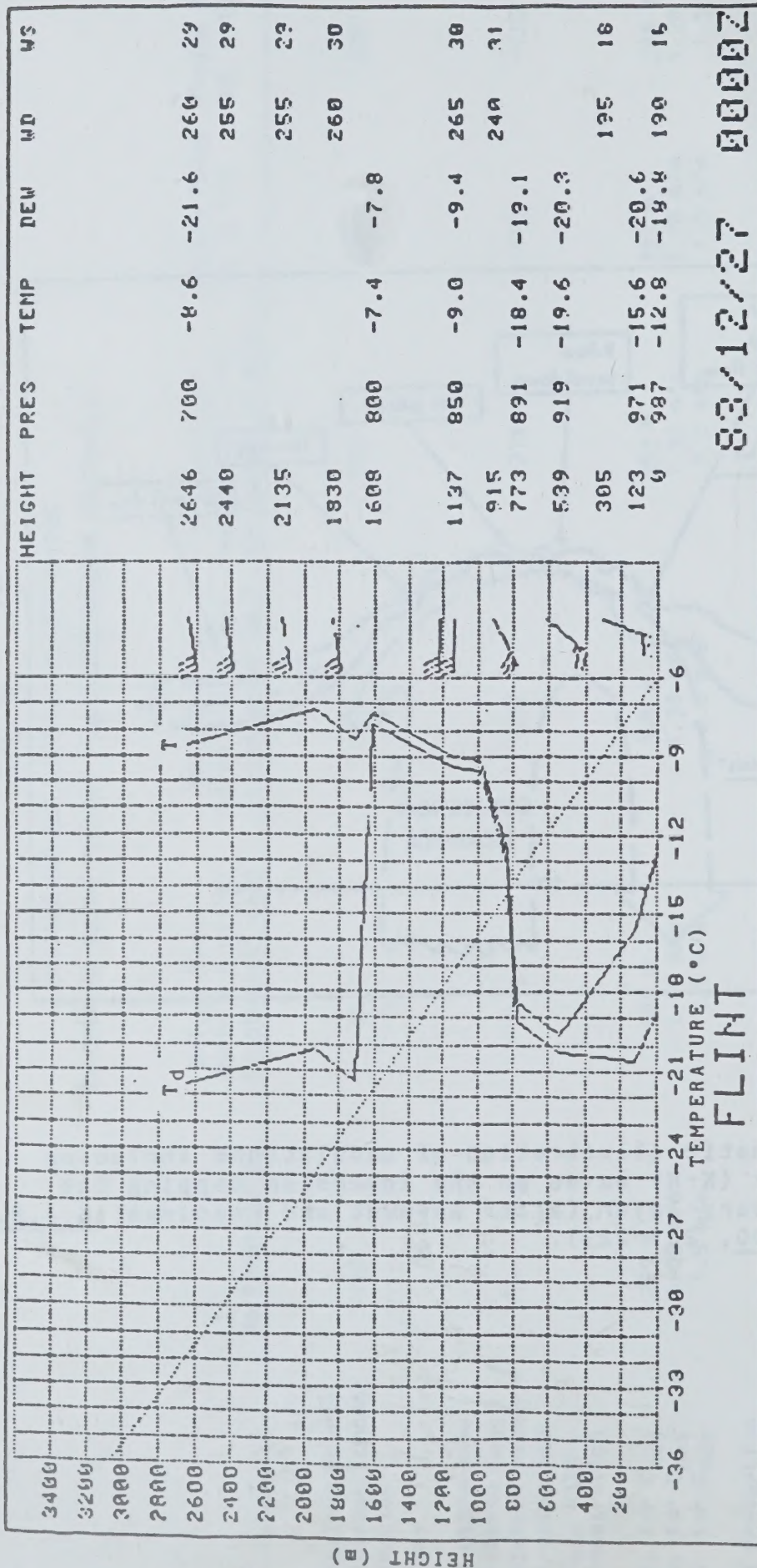
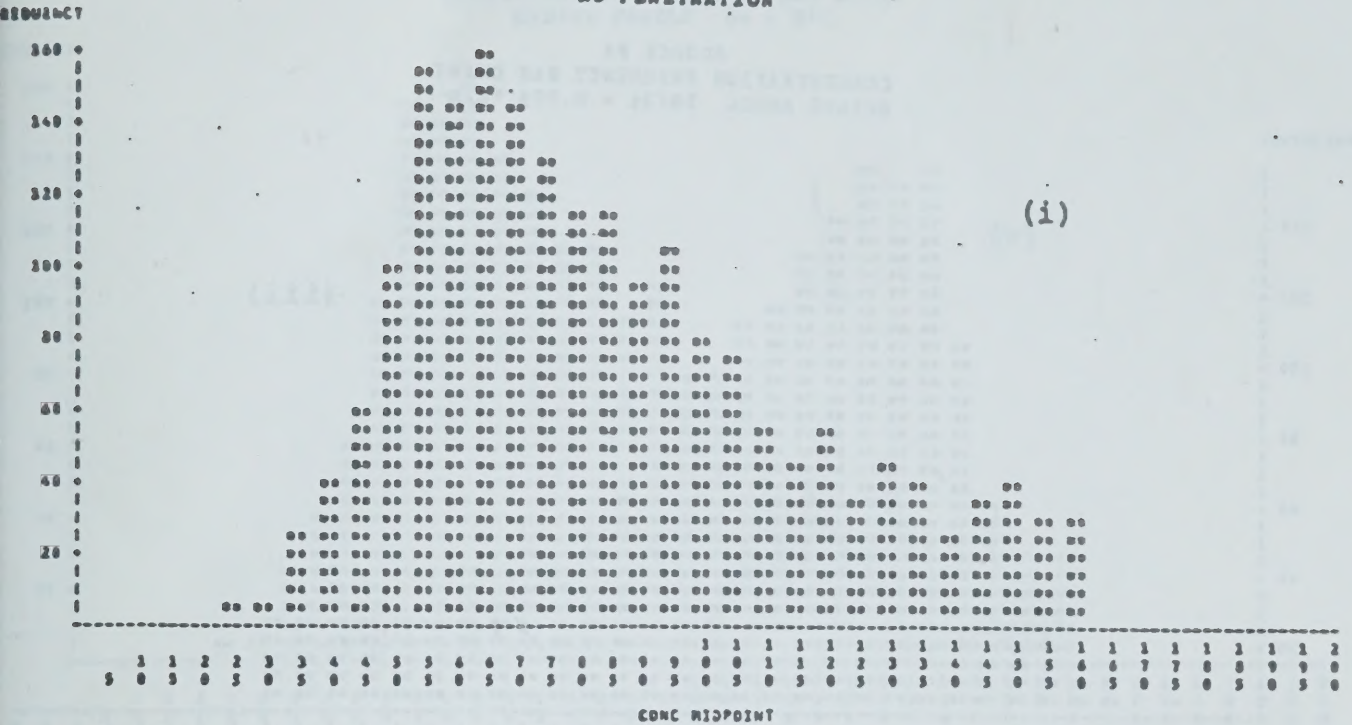


Figure 2: Vertical profile of temperature (T) and dew point temperature (Td) measured by the 0002, December 27, 1983 rawinsonde released from Flint MI. Note the sharp increase in temperature of approximately 11°C over 200 m (temperature inversion) beginning at a height of 800 m above the surface.

SOURCE #1
CONCENTRATION FREQUENCY BAR CHART
NO PENETRATION



SOURCE #1
CONCENTRATION FREQUENCY BAR CHART
BRIGGS MODEL 30/32 - 0.01 °C/m

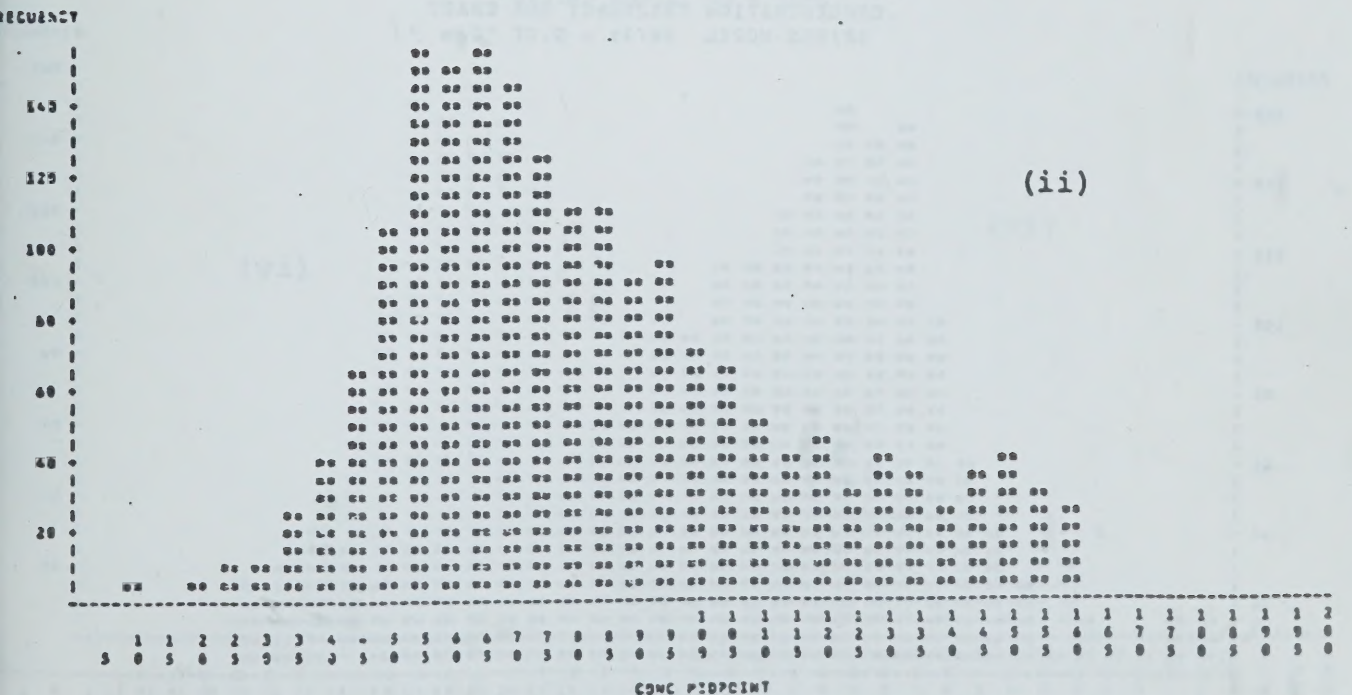
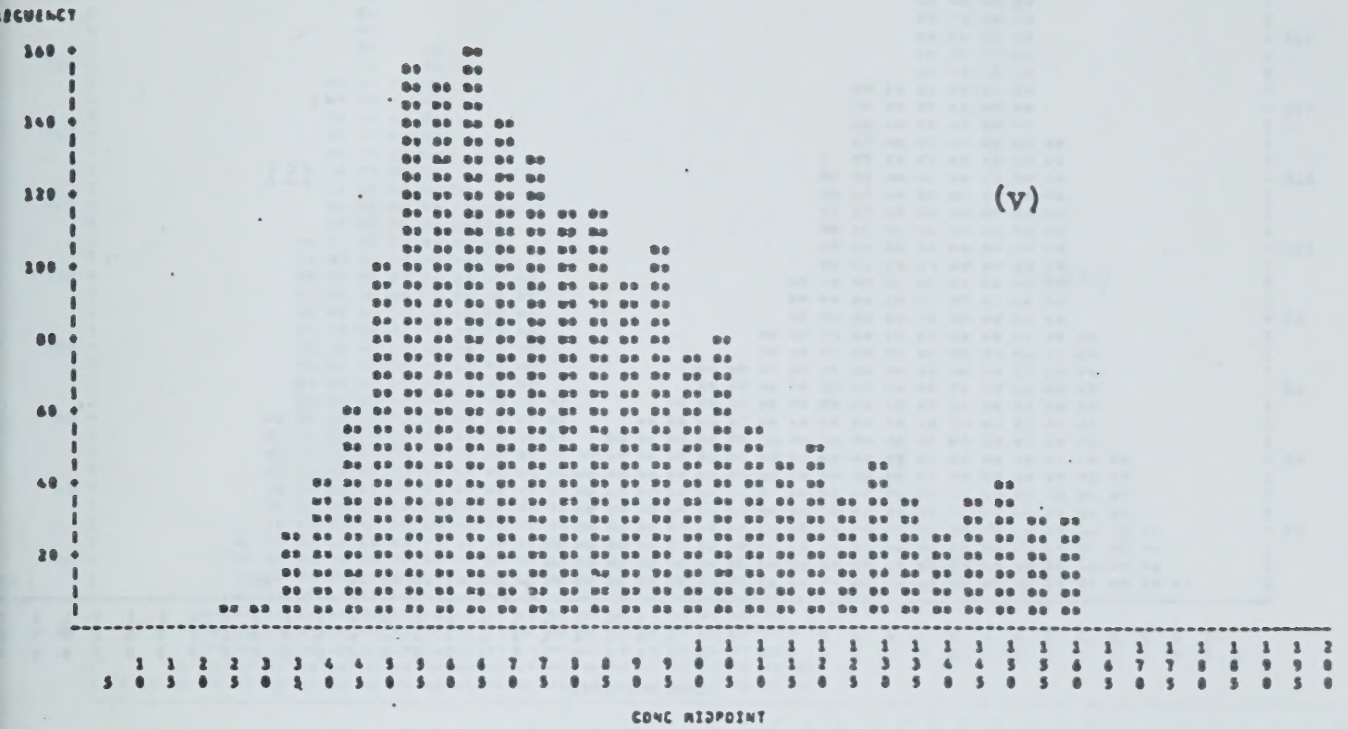


Figure 3: Histogram of the hourly average maximum calculated concentration from source #1. Only periods when the calculated concentration exceeded 5 units are plotted. The vertical axis has units of hours. Each bar on the horizontal axis spans five concentration units. The plume penetration model used for the different sets of concentration calculations is indicated above the respective histograms.

SOURCE #1
CONCENTRATION FREQUENCY BAR CHART
MANINS MODELS $\Delta\theta = 5^{\circ}\text{C}$



SOURCE #1
CONCENTRATION FREQUENCY BAR CHART
MANINS MODEL $\Delta\theta = 10^{\circ}\text{C}$

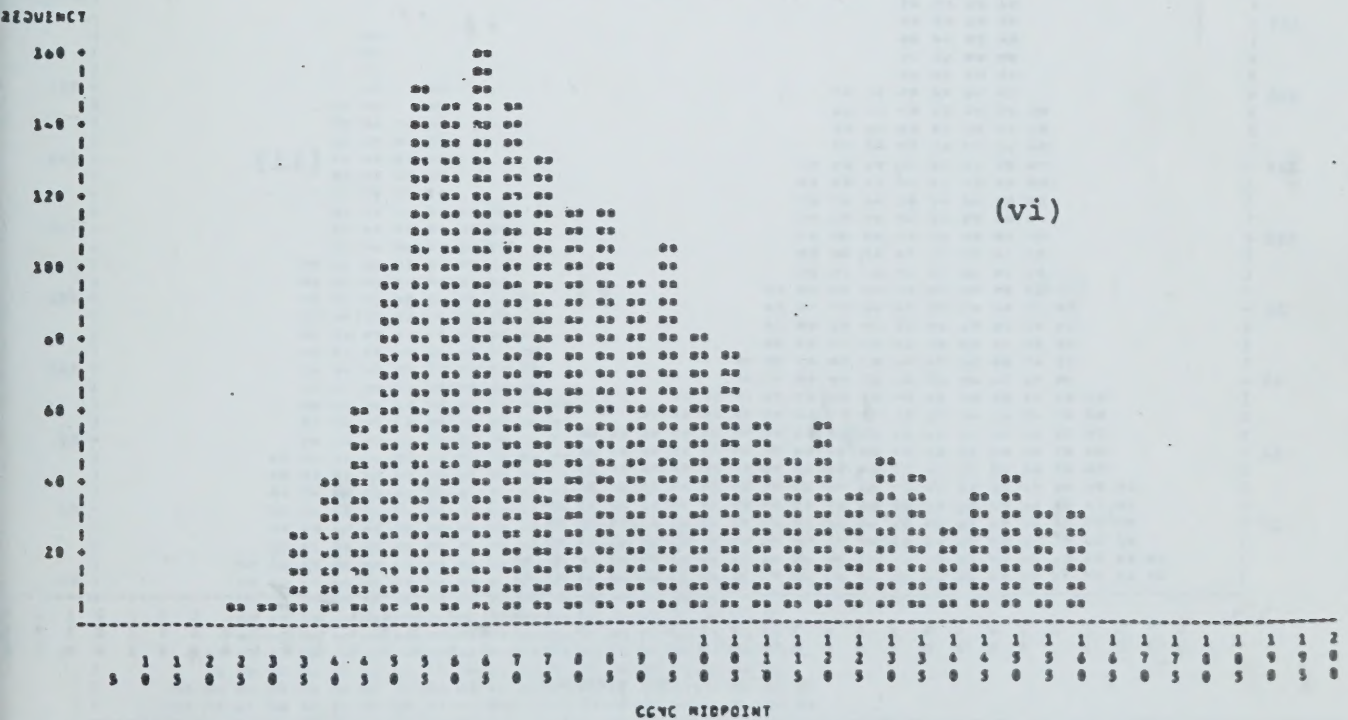
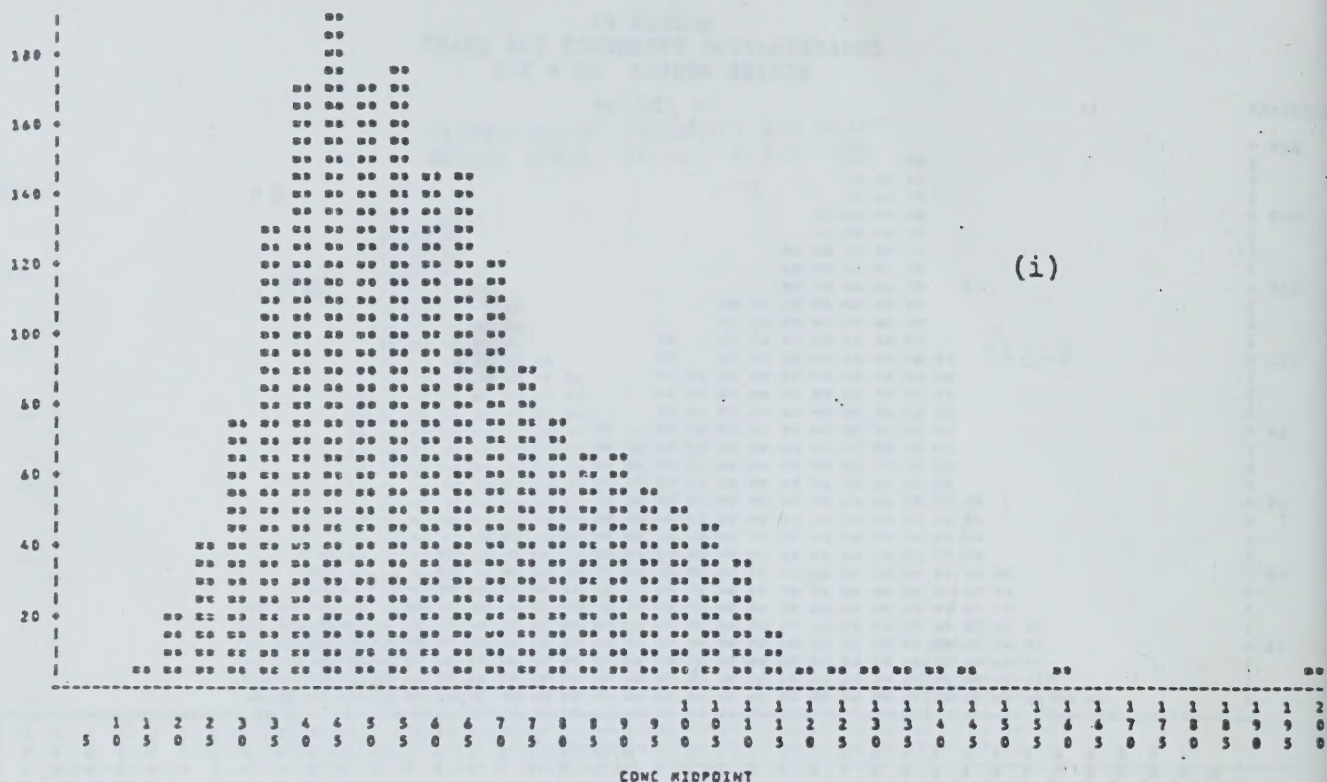


Figure 3: Histogram of the hourly average maximum calculated concentration from source #1.

FREQUENCY



SOURCE #2
CONCENTRATION FREQUENCY BAR CHART
BRIGGS MODEL $\sigma/\sigma_z = 0.01$ °C/m

FREQUENCY

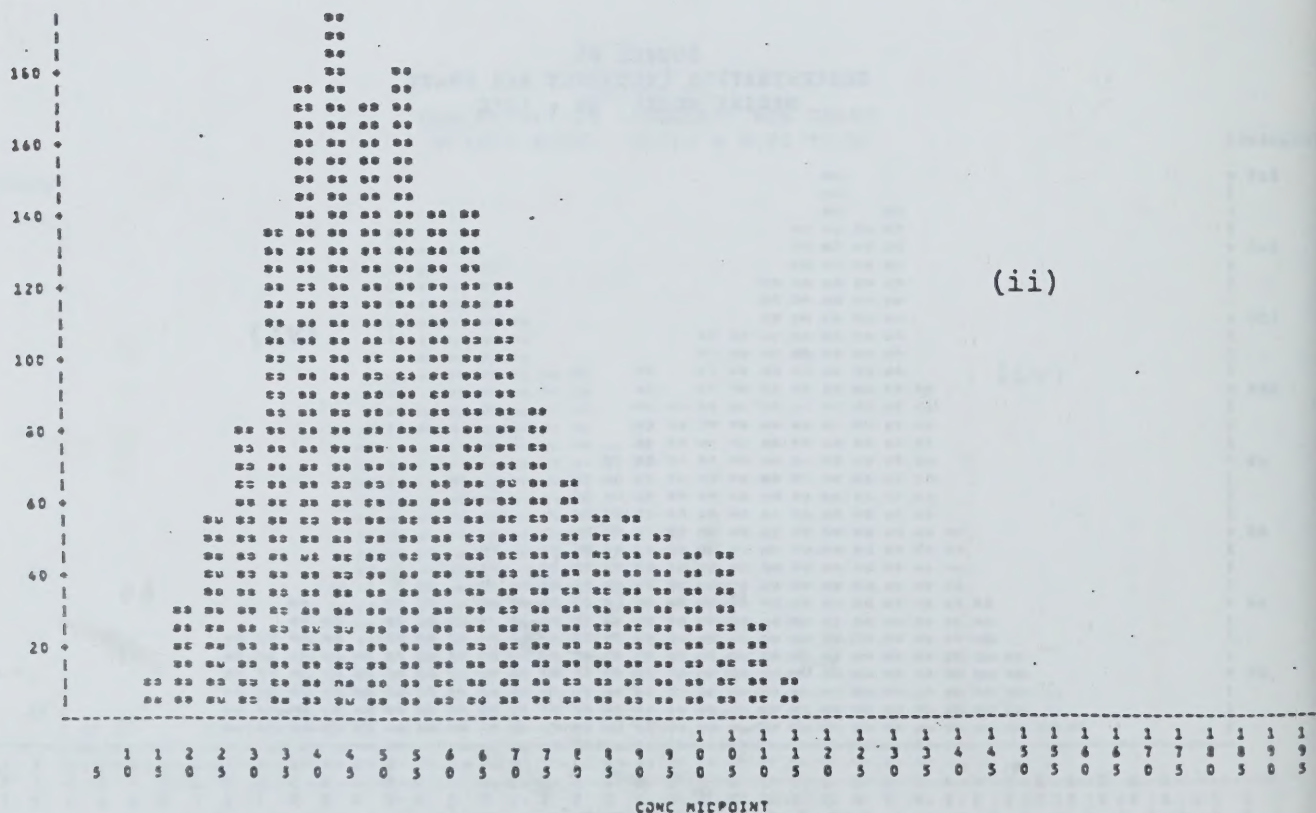


Figure 4: Histogram of the hourly average maximum calculated concentration from source #2. Only periods when the calculated concentration exceeded 5 units are plotted. The vertical axis has units of hours. Each bar on the horizontal axis spans five concentration units. The plume penetration model used for the different sets of concentration calculations is indicated above the respective histograms.

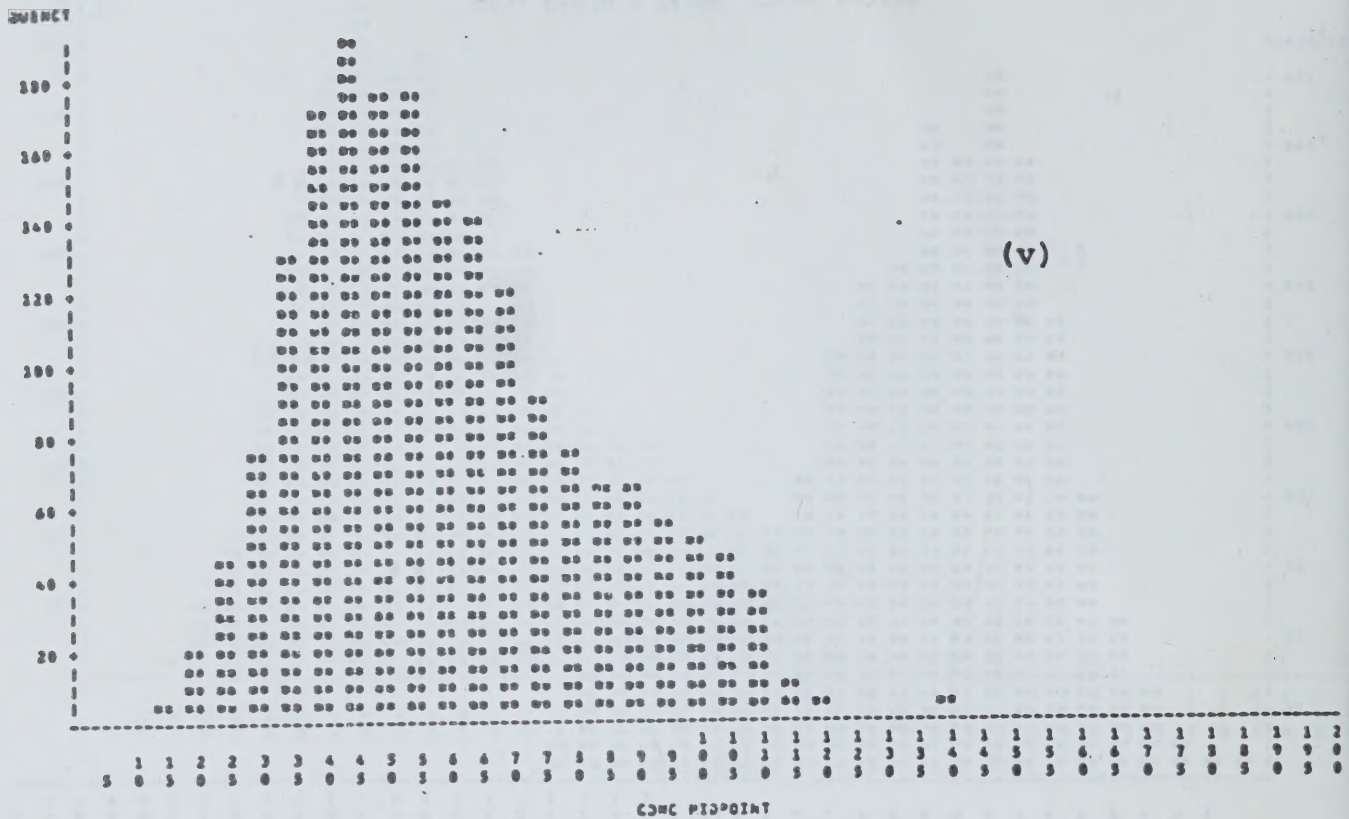
- 139 -



Figure 4: Histogram of the hourly average maximum calculated concentration from source #2.

CONCENTRATION FREQUENCY BAR CHART
MANINS MODELS Δ0 - 5°C

-140-



SOURCE #2
CONCENTRATION FREQUENCY BAR CHART
MANINS MODEL Δ0 - 10°C

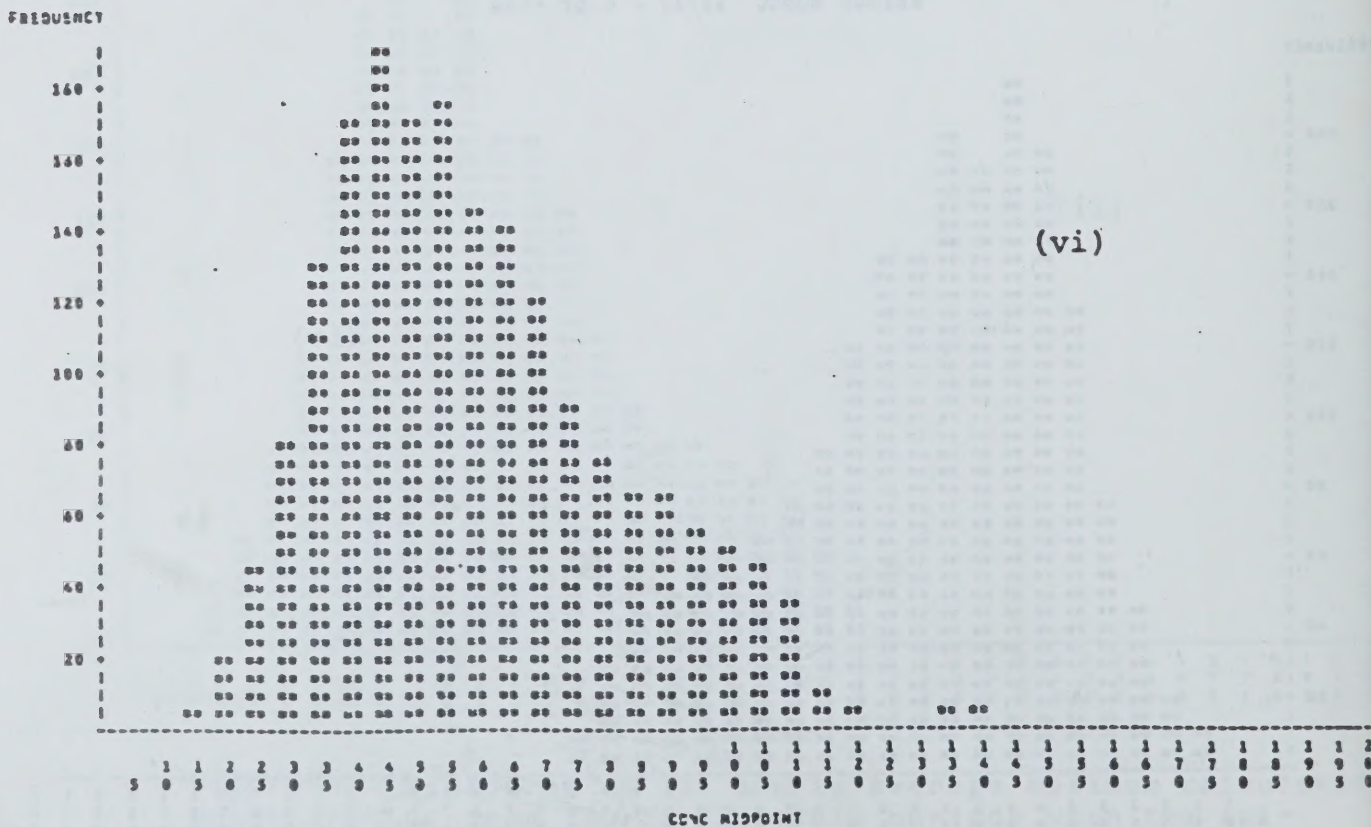


Figure 4: Histogram of the hourly average maximum calculated concentration from source #2.

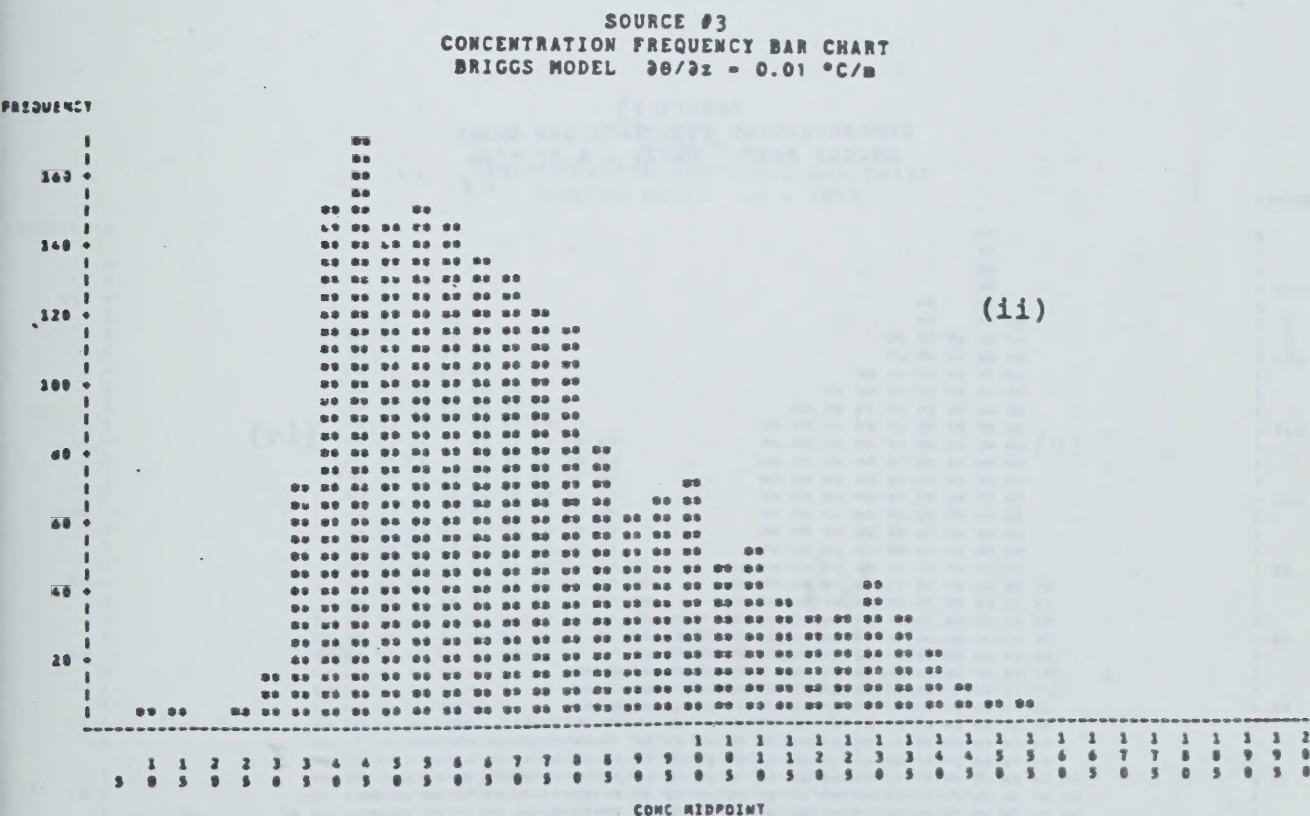
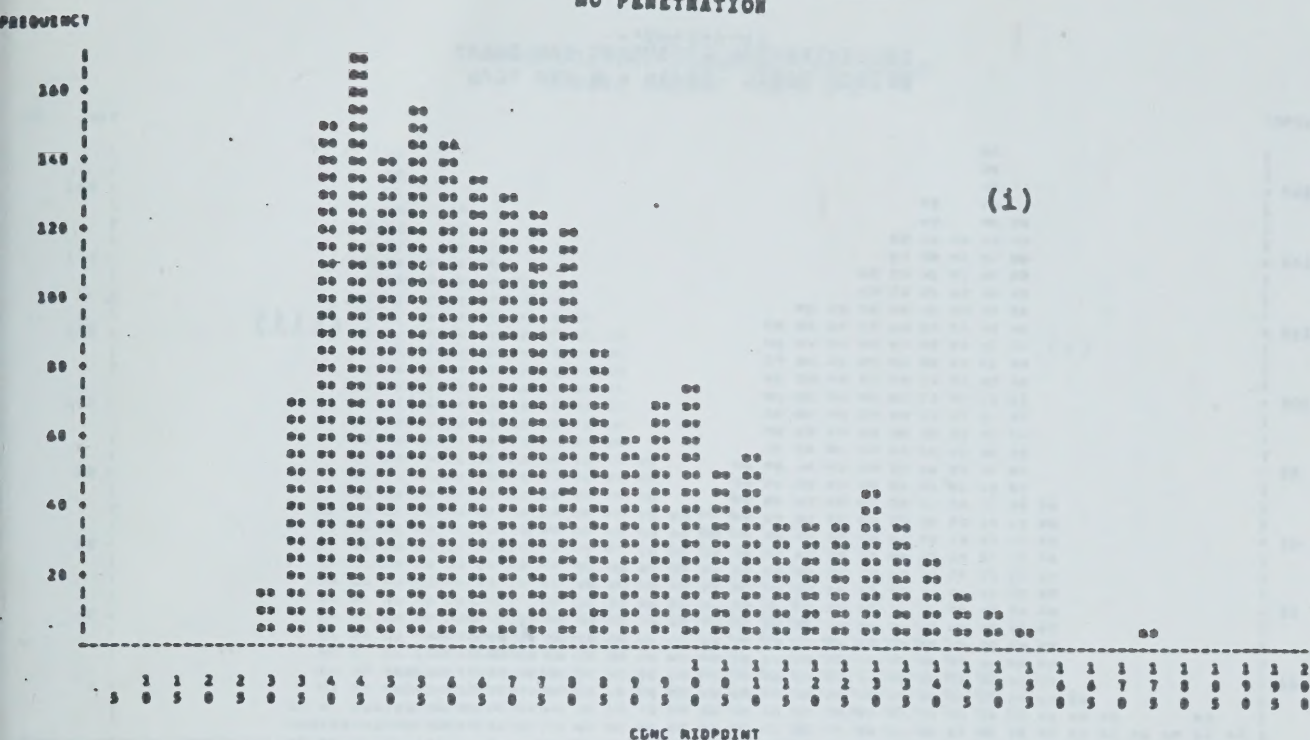
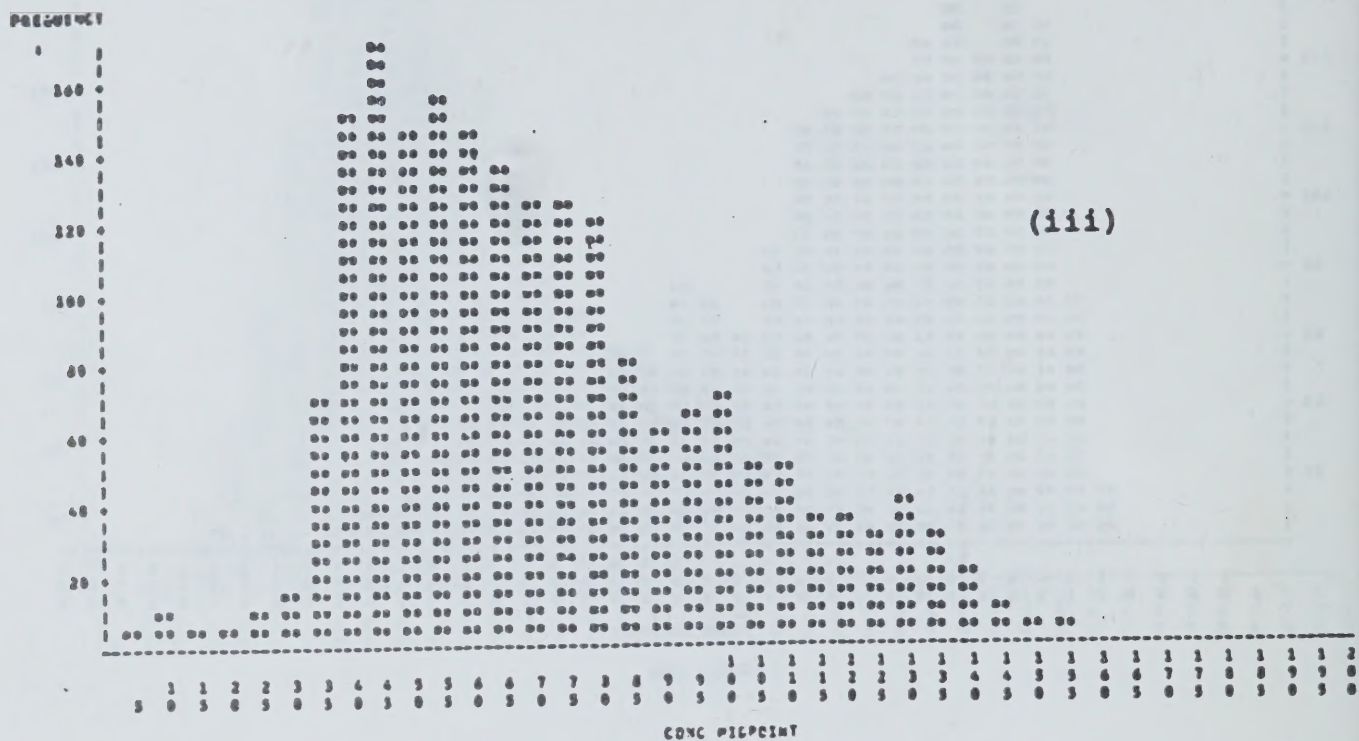


Figure 5: Histogram of the hourly average maximum calculated concentration from source #3. Only periods when the calculated concentration exceeded 5 units are plotted. The vertical axis has units of hours. Each bar on the horizontal axis spans five concentration units. The plume penetration model used for the different sets of concentration calculations is indicated above the respective histograms.

CONCENTRATION FREQUENCY BAR CHART
BRIGGS MODEL $\sigma/\sigma_z = 0.023$ °C/m



SOURCE #3
CONCENTRATION FREQUENCY BAR CHART
BRIGGS MODEL $\sigma/\sigma_z = 0.07$ °C/m

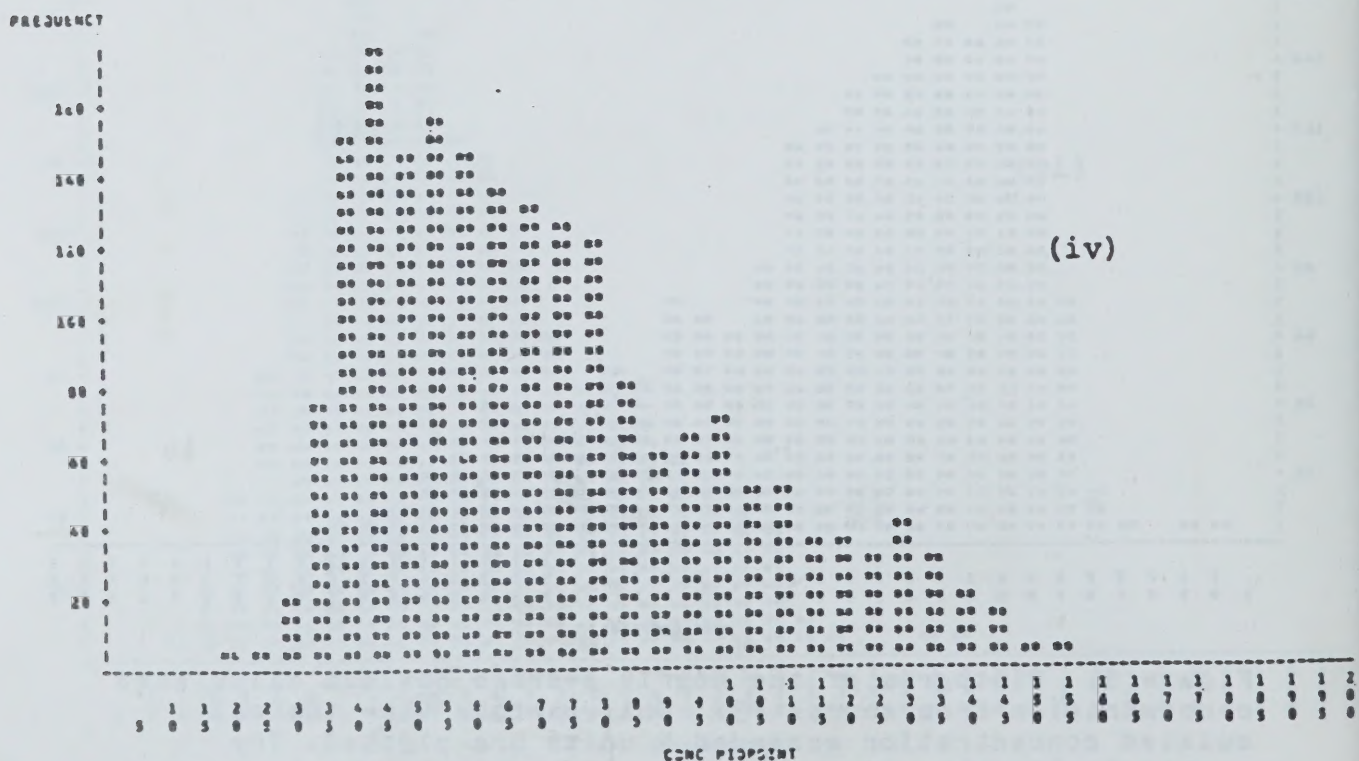


Figure 5: Histogram of the hourly average maximum calculated concentration from source #3.

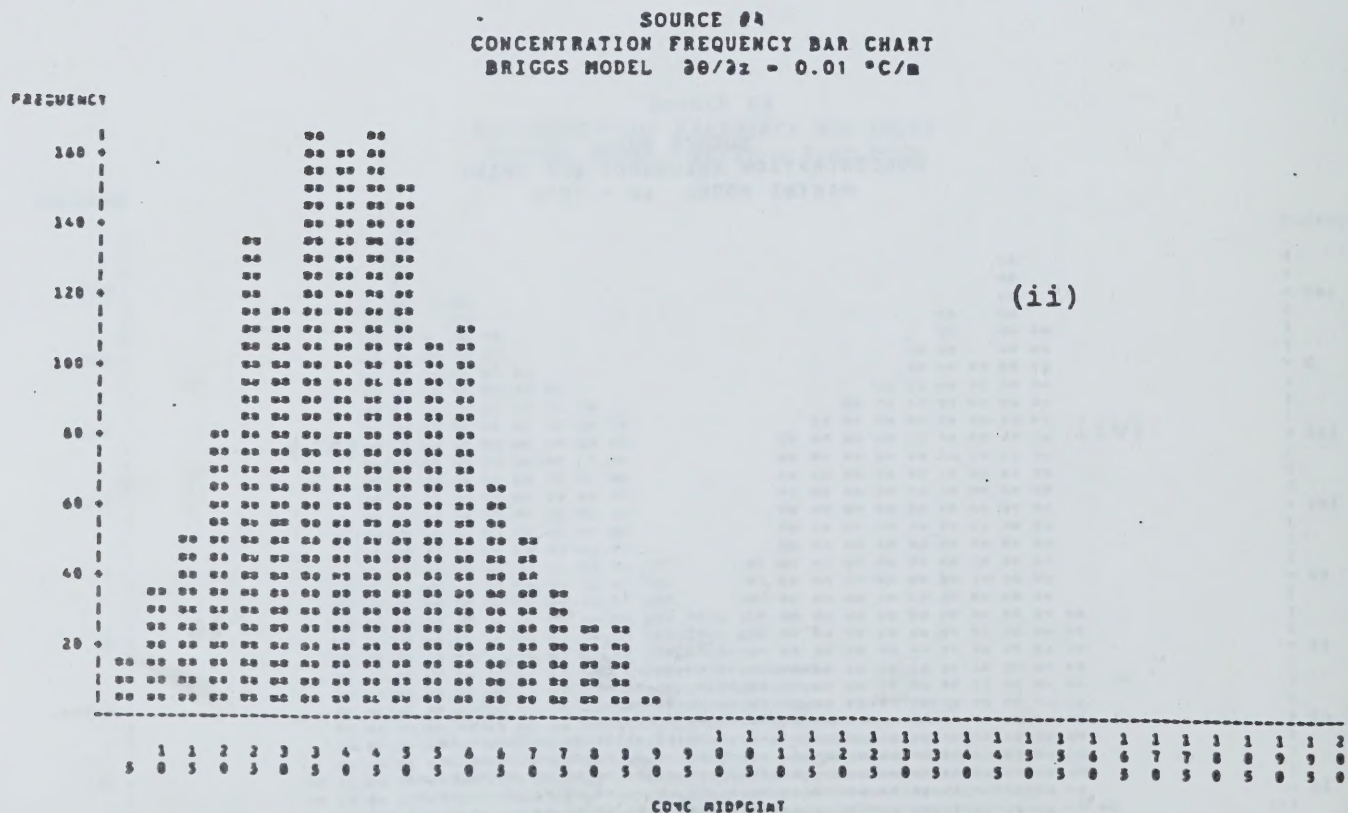
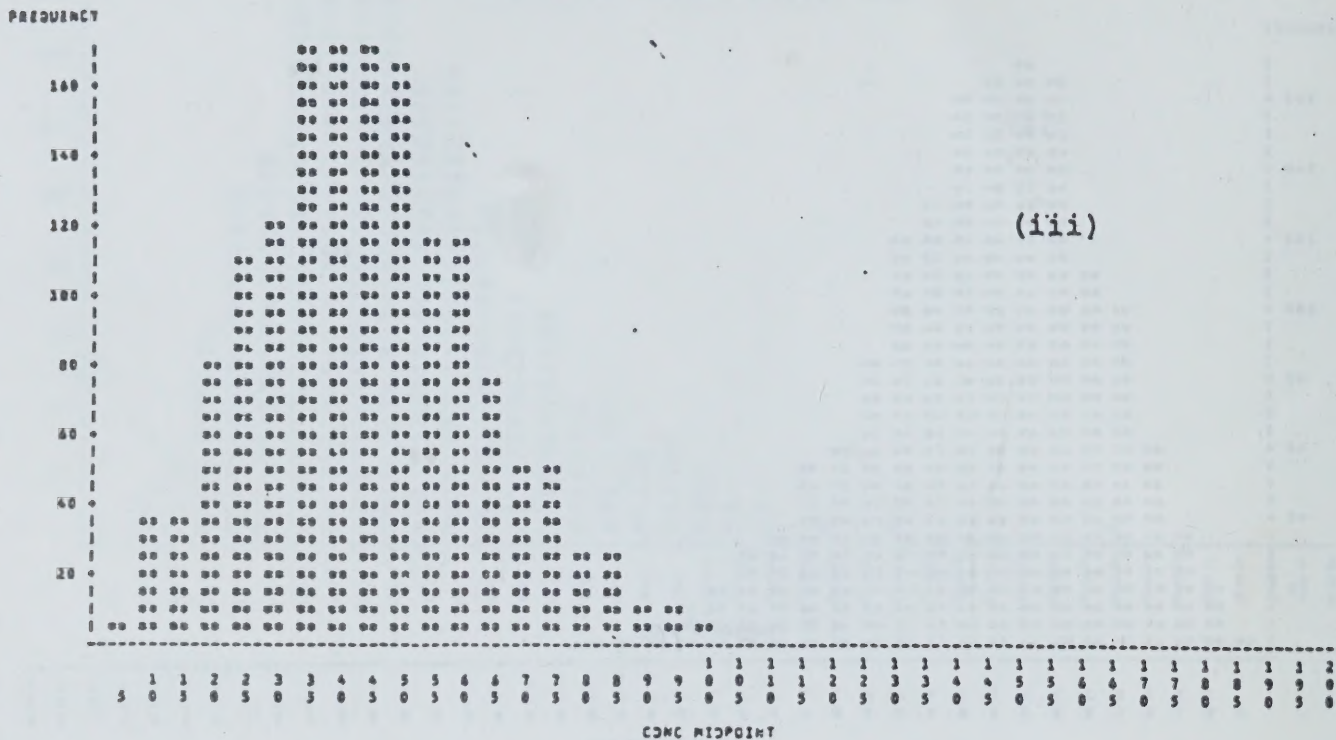


Figure 6: Histogram of the hourly average maximum calculated concentration from source #4. Only periods when the calculated concentration exceeded 5 units are plotted. The vertical axis has units of hours. Each bar on the horizontal axis spans five concentration units. The plume penetration model used for the different sets of concentration calculations is indicated above the respective histograms.



Figure 6: Histogram of the hourly average maximum calculated concentration from source #4.

SOURCE #4
CONCENTRATION FREQUENCY BAR CHART
BRIGGS MODEL 30/3z = 0.023 °C/m



SOURCE #4
CONCENTRATION FREQUENCY BAR CHART
BRIGGS MODEL 30/3z = 0.07 °C/m

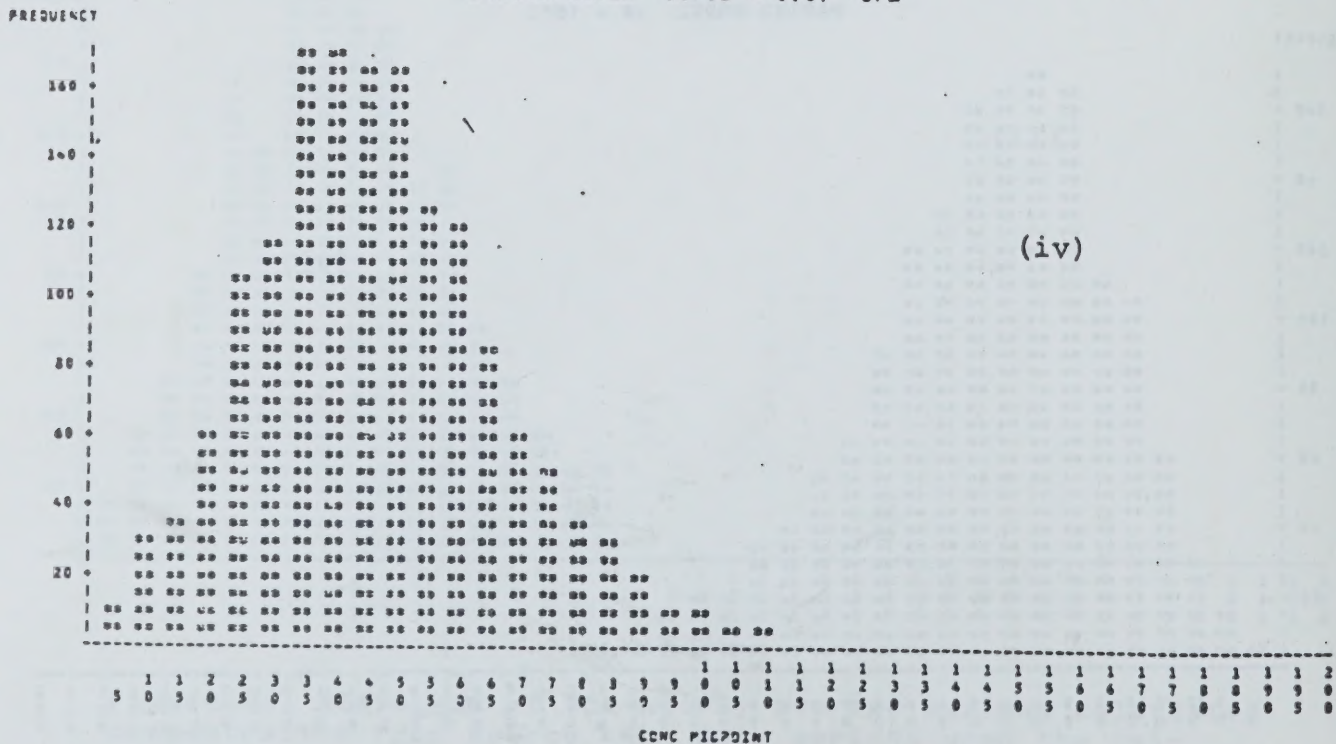
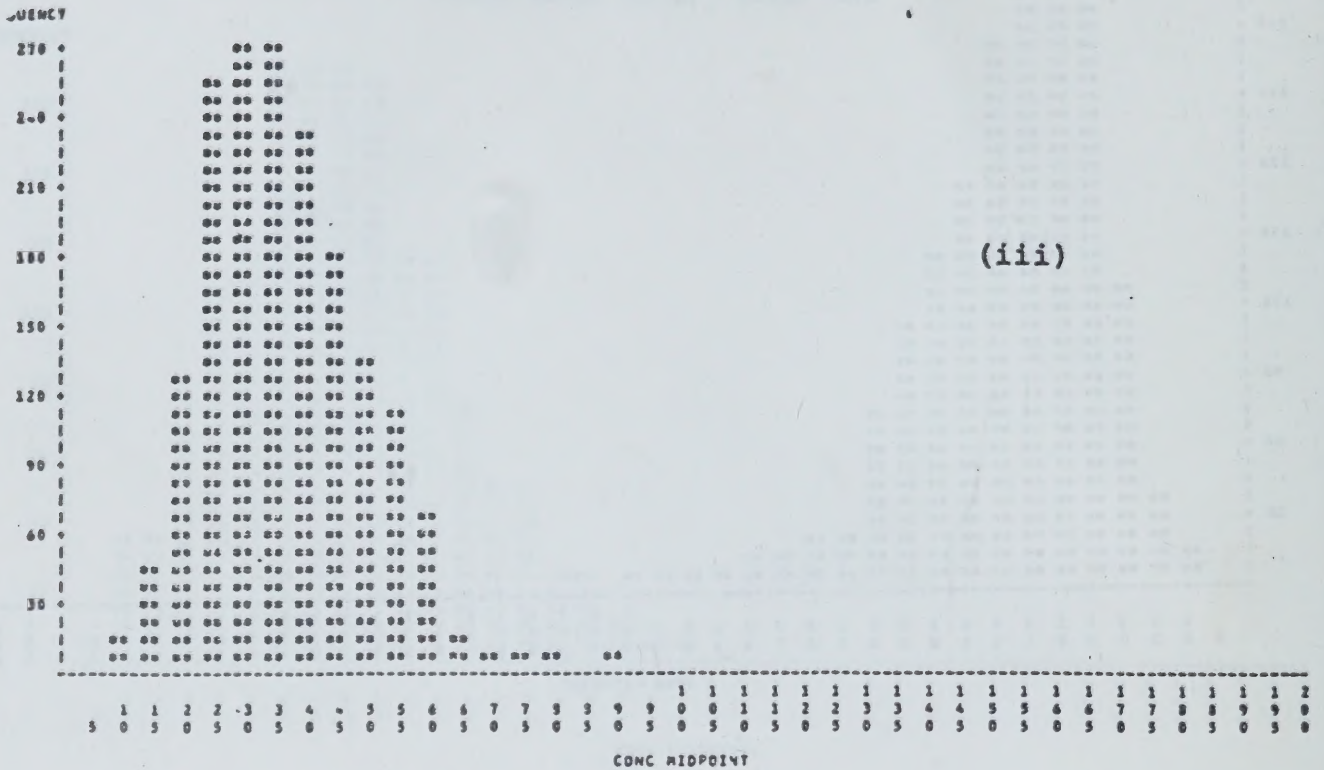


Figure 6: Histogram of the hourly average maximum calculated concentration from source #4.



Figure 7: Histogram of the hourly average maximum calculated concentration from source #5. Only periods when the calculated concentration exceeded 5 units are plotted. The vertical axis has units of hours. Each bar on the horizontal axis spans five concentration units. The plume penetration model used for the different sets of concentration calculations is indicated above the respective histograms.

SOURCE #5
CONCENTRATION FREQUENCY BAR CHART
BRIGGS MODEL $\sigma_y/\sigma_z = 0.023 \text{ } ^\circ\text{C}/\text{m}$



SOURCE #5
CONCENTRATION FREQUENCY BAR CHART
BRIGGS MODEL $\sigma_y/\sigma_z = 0.07 \text{ } ^\circ\text{C}/\text{m}$

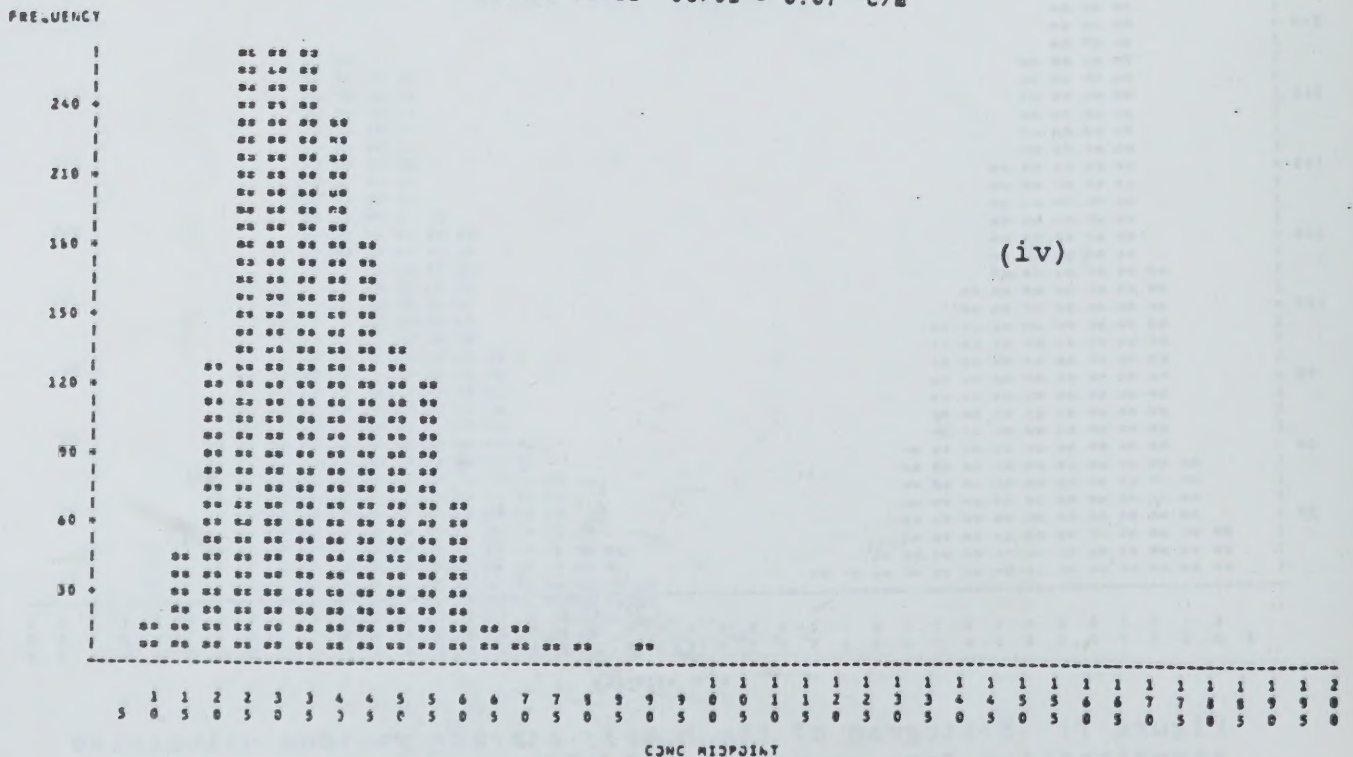


Figure 7: Histogram of the hourly average maximum calculated concentration from source #5.

A PROPOSAL FOR
MODELLING AIR QUALITY DUE TO
CONTAMINANT RELEASES FROM A LOCATION
ON OR NEAR A
BUILDING

INTRODUCTION:

Accurate estimates of concentrations of pollutants from sources which are influenced by the presence of nearby buildings can only be made for very simple building structures. The definition of simple building structures is described in the following paragraphs. Most buildings do not conform to this definition of a simple building. In these cases engineering estimates of concentrations in the presence of buildings can nevertheless be made. This report describes the equations applicable for simple buildings and the criteria for their application to structures which are not so simple.

Definition of 'Simple Building or Structure'

The modelling approach described in this report is proposed for estimating the air concentration of a contaminant downwind from a release point on or near a building or structure with horizontal and vertical dimensions which are comparable in size. As a tentative guideline it is recommended that the maximum horizontal face of the building or structure ($L_{\max}$) not be greater than five times the minimum horizontal face of the structure ($L_{\min}$). The height (H_B) of the building or structure should be between $\frac{1}{2}$ and 2 times the minimum horizontal length scale of the building. In addition, the building or structure should be approximately rectangular in shape without complicated roof lines or distortions in the overall shape of the building or structure.

These guidelines for relative building dimensions are proposed based on a survey of the evaluation of several simple modelling methods for contaminant concentrations downwind of influencing structures [e.g.

Huber, (1984) Fackrell (1984), Ogawa et al (1983)]. The majority of observational data are for simple rectangular or cylindrical structures. Hence, the testing of modelling concepts for dispersion as influenced by buildings or structures have only been assessed for such simple structures. For releases on or near buildings or structures which do not conform to these guidelines, it is recommended that physical modelling be used to assess contaminant concentrations in the vicinity of the building or structure.

Buildings and other structures usually exist in clusters. Within a cluster of buildings the flow pattern may be very complicated. Only physical modelling or field studies are suitable for assessing local pollutant dispersion in such settings.

In the far wake region (i.e. well beyond the downwind extent of the wake recirculation cavity) of a tightly clustered group of structures with similar heights, buildings or structures have been viewed as a single effective structure [e.g. Huber (1984)]. However, no guidelines are available to define "tightly clustered" or to determine effective structure dimensions, as these may be complicated functions of the flow orientation with respect to the buildings.

Emission Height Relative to the Building/Structure Height

It is proposed that the dispersion of material released on or near a building or structure may be assumed to be influenced by structure-induced turbulence if the release height after compensation for stack-induced downwash is less than two times that building height (H_B). Otherwise, the release may be treated as if the building or structure is not present. For structures within the guidelines proposed above, if material is released at heights less than $2H_B$ it may be trapped within the building wake recirculation. This estimate is based on Wilson's (1979) parameterization of depth of the roof recirculation zone for simple structures. Material released in the recirculation cavity can be well-mixed within this region prior to dispersion downwind.

Definition of 'Near'

The release of a contaminant in close proximity to a building will influence the dispersion of the material. For a source upwind of a building, Wilson and Netterville (1978) found that a simple structure's influence on the contaminant dispersion extended upwind a distance of approximately 1.3 times the building height. For material released at distances greater than $1.3 H_B$ upwind of the building, Wilson and Netterville (1976) noted that the most important effect of the structure on an incident plume is to enhance the mixing of the contaminant. In this case, it is proposed that the concentration of contaminant for receptors on the structure may be estimated by using the maximum concentration calculated without including building effects on the surface defined by the upwind face of the structure.

Material released at a distance of less than $1.3 H_B$ from the upwind edge of the building may be entirely trapped in the region of distorted flow and high turbulence which can form around the structure.

The region of building-induced turbulence wraps around the structure; therefore, dispersion of material released near the sides of a structure may be influenced by the flow distortions around the building. Studies by Penwarden and Wise (1975) [as reported by Hosker (1984)] indicated the cross-wind extent of the flow distortion at the sides of a structure may extend a distance approximately equal to the building width (in the cross-wind direction) from the side of the structure. This distance may be less for buildings on which the flow re-attaches to the sides of the structure following distortion at the upwind face of the building.

On the downwind side of a structure or building there will be a wake cavity zone. Within this region the turbulent flow pattern is very complex. The maximum downwind extent of the cavity for a structure with dimensions within the guidelines proposed above is approximately five times the building height [based on Hosker's (1979) parameterization cavity length]. As noted above, the high turbulence

region may extend to a height of approximately $2H_B$ and a cross-wind distance of approximately equal to the building width (in the cross-wind direction) beyond the structure.

Hence, for the modelling methods proposed in this document an emission source will be considered to be near a building or structure if it is located within a horizontal distance of five times the building height or once the crosswind building width (whichever is greater) from the edge of the structure. It will be assumed that material released at a height of less than $2H_B$ within this distance is trapped in the high turbulence region and is well mixed within this region prior to dispersing downwind.

Concentration Calculation

It is proposed that the concentration of a contaminant released on or near a building at receptors on the building, or within the building's region of high turbulence, be estimated using the expression:

$$C = \frac{Q}{a_1 u A_p} \quad (1)$$

proposed by Barry (1964) and Meroney (1982). Currently, this model is employed in the Appendix to Regulation 308, Section 2, Subsection A with $1/a_1 u = 0.6$ and $A_p = L^2$. It is recommended that Eqn. (1), in the form it appears in Regulation 308, be retained for on and near building receptors. Here L is the straight line distance in meters to the nearest receptor from the source.

To calculate concentration of a contaminant released on or near a building at receptors downwind, and beyond the region of high turbulence induced by the structure, it is recommended that the release be treated in the following manner. First, assume that the release is effectively at ground level. Second, assume that the initial vertical mixing of the material by building-induced turbulence has resulted in contaminant being mixed to a mean height, $\bar{z}$, equal to $\frac{1}{2}$ the

building height. Then apply the surface release modelling described in Chapter V, Air Pollution General Regulation Workshop November, 1985 (amended June, 1986), with $\bar{z} = \frac{1}{2} H_B$ to calculate the virtual source location, x_0 , relative to the release point.

Third, assume that the building-induced turbulence will also enhance the initial cross-wind spread dispersion of material released on or near the building such that the initial cross-wind spread parameter is proportional to width of the building exposed to wind, W_B .

Defining

$$\sigma_{y_0} = \frac{1}{4} W_B,$$

subsequent lateral spread may then be calculated using

$$\sigma_{y_{TOTAL}} = (\sigma_{y_0}^2 + \sigma_y^2)^{\frac{1}{2}},$$

where formulation of the lateral dispersion parameter σ_y is given as a function of atmospheric stability in Chapter 5.

Finally, concentration may be calculated at the downwind receptor location (x,y,z) using the modelling method outlined in Chapter 5 for surface releases and using $\sigma_{y_{TOTAL}}$ in place of σ_y .

Criteria for Application of Equation (1) to Other Buildings or Structures

Since most buildings will not conform to the above definition of simple buildings, the following procedure is recommended for general application:

1. Compute the concentration according to equation (1) using the value of L , which is the minimum of:
 - a) the distance to the nearest receptor; or,
 - b) the minimum cross-sectional dimension of the building exposed to the wind.
2. If the computed concentration is greater than or equal to $\frac{1}{2}$ of the air quality criterion value for the pollutant, and the building or structure does not conform to the simple building definition, then physical modelling is recommended.

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A PROPOSED GUIDELINE FOR PHYSICAL MODELLING OF SOURCES IN COMPLEX SETTINGS

This document describes proposed criteria to define a setting sufficiently complex to recommend wind tunnel or water tank modelling (i.e. physical modelling) in addition to the mathematical modelling described in Chapter V of Air Pollution General Regulation Workshop November, 1985, entitled "Air Quality Models Suitable for Regulatory Application". The basic requirements for adequate physical modelling and several alternatives to physical modelling are also outlined.

Definition of a "Complex Setting"

The two settings for which physical modelling might be recommended are:

1. A major development in a complex urban situation involving clusters of buildings or buildings with non-simple geometry.
2. Cases where a source is located in complex terrain.

Guidelines to define a simple building are provided on pp. 149-150. It is proposed that physical modelling be performed for a major development in a complex urban setting if the release height of the contaminant after compensating for stack-induced downwash is less than two times the height of the building or of nearby buildings, where "near" is defined in the appendix listed above.

The second general circumstance for which physical modelling is recommended occurs when the terrain around a pollution source is complex. Significant terrain features near a source can affect the dispersion of material from that source and the range and frequency of occurrence of meteorological circumstances at the site.

It is proposed that terrain features are sufficiently complex to warrant physical modelling if the following conditions hold.

1. The release height of the contaminant is less than two times the maximum terrain height (h_{3max}). The maximum terrain height is defined as the difference between the highest height level (including tree tops) and the lowest height level within a distance of 20 times the stack height.
2. In addition, it is proposed that the gradient of terrain height with distance, Δx , from the source (i.e. $\Delta h/\Delta x$) must be greater than $1/5$. This criterion means that gently sloping terrain would not be considered to be sufficiently complex to recommend physical modelling. $\Delta h/\Delta x \geq 1/5$ is recommended as the terrain gradient criterion based on studies such as those by Briggs (1981) and Mickle et al. (1981) which show significant alterations of wind speeds and directions with terrain slopes of $\sim 1/5$ or $1/6$.

Meteorological data are needed as input for either physical modelling or for running the set of mathematical dispersion models proposed in Chapter V of Air Pollution General Workshop, November 1985. Since the range and frequency of occurrence of meteorological data can be affected by terrain features such as ridges, these effects should be considered when compiling meteorological data for complex sites.

Description of Physical Modelling

Physical modelling involves laboratory studies of dispersion using a scaled-down model of a source and the terrain features. These studies can be performed in either a wind tunnel or in a water tank. Because a scale model of the source and its environment is used in the wind tunnel or water tank, it is necessary that the characteristics of the wind flow and the thermal regimes in the experimental setup correspond to the scale of the model. For example, spatial variations in the mean wind flow pattern caused by the complexity of the setting should be

reduced in scale by the same factor that the model is scaled, compared to the actual site dimensions.

Several non-dimensional numbers, referred to as similarity numbers, are used to characterize the flow and thermal features in any fluid medium. These similarity numbers, which are combinations of the physical parameters of the system (i.e. flow speed, length scales, temperature, etc.) are constructed in such a way that they describe the physical processes which occur in the fluid. For wind tunnel or water tank studies of dispersion in complex terrain, the important similarity numbers are the Reynolds, Froude and Prandl numbers [Snyder (1981) and Snyder (1972)]. When working with scale models in wind tunnels or water tanks care must be taken that these similarity numbers should correspond to values in the atmosphere for the site in question. Snyder (1981) has provided a good description of the application of similarity numbers to wind tunnels or water tanks in a variety of circumstances.

A wind tunnel simulation of atmospheric dispersion has the advantage that the fluid medium is the same. Correspondingly it is easier to produce adequate similarity number matching. On the other hand, water tanks allow good flow visualization by using dyes in the fluid. Also, it is a little easier to simulate non-neutral atmospheric stability conditions in a water tank than in a wind tunnel, although it can be done in both experimental setups [Ueda et al. (1986), Willis and Deardorff (1981) and Porek and Cermak (1984)].

It is recommended that a facility capable of handling stable, neutral and convective conditions be used when simulations are done for a source in complex terrain. There are wind tunnel facilities in the U.S. and Japan which can perform simulations for stable or convective conditions [Porek and Cermak (1984) and Ueda et al. (1986)] and there is no reason to believe that existing Canadian facilities cannot be modified. If only neutral simulations are undertaken numerical model results for convective, neutral and stable cases described in Chapter V of Air Pollution General Workshop November, 1985, should be compared

with physical modelling results for the neutral simulation, to develop specific worst-case concentrations.

Alternatives to Physical Modelling

For sites that are sufficiently complex to warrant physical modelling several alternatives are proposed. Any one of these alternatives could be used by the proponent in place of physical modelling simulations.

1. One alternative is to do a comprehensive field study at the proposed site. Such a field study would include measurements of the local meteorology and pollution dispersion characteristics at a number of receptors around the source. The measurements would have to be taken over a long enough time period to cover the range of possible meteorological conditions at the site (≥ 1 year).
2. A second alternative suggested as a conservative estimate for elevated sources in complex terrain is to calculate ground level concentrations along the varying terrain using a reduced plume height. Since complex terrain situations have the potential to affect the centreline height of the plume, it is recommended that ground level concentrations be calculated using a plume height equal to half the centreline plume height calculated for flat terrain. The flat terrain plume height would be calculated as the sum of the stack height and plume rise as outlined in Chapter V of Air Pollution General Workshop. Formulae for deriving concentrations as a function of distance downwind and height above the source location ground level are provided in the report for stable and neutral conditions. It is recommended that ground level concentrations at the height of the varying terrain be calculated for receptors within a radius defined by the nearest location, where the terrain height is greater than or equal to half the flat terrain plume height. It is further recommended that the maximum radius for which these receptor calculations need be performed is 100 times the stack height.

Maximum ground level concentrations would then be derived as the larger of the maximum receptor concentration for neutral and stable conditions outlined above or convective calculations for an elevated source in flat terrain as described in the report.

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MODELLING AIR QUALITY FOR RELEASES IN A LAKESHORE SETTING

The lakeshore marks an almost immediate change in surface roughness, temperature and evaporation to which the low-level air flow must react. Hence, these changes in surface conditions affect the transport and dispersion of contaminants released near the lakeshore.

Diffusion During On-Shore Flow

Modelling diffusion of a contaminant released near a lakeshore during on-shore flow is complicated by the transition of surface conditions from lake to land. On-shore flow of stable air (frequently stabilized by heat loss at the surface during advection over a relatively cold lake surface) to a warm land surface heated by the sun creates conditions ideal for continuous fumigation of elevated contaminant releases. As the flow crosses the lake-land interface the surface changes result in the formation of internal boundary layers. The thermal internal boundary layer which forms as a result of surface heating over land gradually deepens inland from the shore. Plumes which are released into the stable air near the shoreline can eventually be transported inland and become entrained in the deepening unstable (thermal internal) boundary layer. The rapid mixing of the plume to ground following its intersection with the thermal internal boundary layer may persist for several hours and, hence, is referred to as continuous fumigation. The final section of this report outlines a model suitable for estimating contaminant air concentrations downwind from a near shoreline elevated release.

A second dispersion regime which may occur for releases near a shoreline during on-shore flow is plume trapping.

The thermal internal boundary layer which develops inland from the shoreline may be relatively shallow, compared to the depth of the boundary layer which would exist for the same conditions in the absence of lake effects. Hence, the vertical dispersion of plumes released into this shallow boundary layer will be limited when compared to the vertical dispersion which could occur in a deeper, inland boundary layer. It is recommended that when modelling releases into the thermal internal boundary layer, the boundary layer height at the source location be employed for calculation purposes rather than a boundary layer depth based on inland measurements. Then the models described in Chapter V of Air Pollution General Regulation Workshop November 1985 (amended June 1986), may be employed for assessing the air quality due to releases into the thermal internal boundary layer.

Diffusion During Off-Shore Flow

Modelling diffusion of material released near a lake shore during off-shore flow should include consideration of the potentially intense modification of the boundary characteristics (eg. stability and depth) which will occur when the flow traverses from land to water with a significantly different temperature. For example, when cold, stable air flows over relatively warmer water the airmass can be transformed from stable to neutral or unstable in nature. Hence, when a contaminant is released near a shoreline during off-shore flow, care must be taken in modelling the dispersion of the plume.

The dispersion of a plume over water is not identified as being of as much concern as dispersion over land when assessing air quality at critical receptors.

Defining Near-Shore Sources

It is proposed that the definition of near-shore sources be based on the release height of the contaminant relative to the height of the thermal internal boundary layer. Observational studies have shown that

the height of the boundary layer during on-shore flow may be approximated as

$$H = A x^{1/2},$$

where x is the distance downwind from the shore-line and A is a parameter dependent upon the transition in surface conditions at the lake/land interface. Typically the value of A ranges between 1.5 and 5; hence, the range of plausible thermal internal boundary layer heights at a given inland, source location, x , may be determined. The Ministry of the Environment will provide this value. If the source release height including plume rise is greater than any possible value of H at the source location, the potential for fumigation of the plume must be included in the modelling assessment.

Medium Scale Influences of Large Lakes

In a coastal environment the existence of local circulations, commonly known as lake/land breezes, is well documented. These local circulations develop in response to differential heating and cooling at the land/water interface. During the daytime the land surface temperature rises rapidly due to incoming solar radiation, whereas the water temperature stays almost constant (due to its large heat capacity). The resulting pressure gradient sets up a circulation cell with on-shore winds at lower levels and return flow at upper levels. This process is reversed during the night time with land cooling rapidly to a lower temperature than that of the neighbouring water body. The development of lake/land breezes may modify the local flow pattern such that meteorological data collected at inland sites, or sites in other coastal environments, are non-representative. Hence, care must be exercised when developing a meteorological dataset for modelling releases in a lakeshore setting.

For cases when the source release height is less than the height H calculated in equation 1, it is still necessary to consider the

influence of equation 1 on the convective boundary layer height when compiling a meteorological data set.

A Shoreline Fumigation Model

On-shore flow during the daytime may bring a stable air mass over the water onto a rapidly heating land mass. As the airmass moves inland, it is heated from below and a convective boundary layer develops which is usually referred to as a thermal internal boundary layer (Fig. 1). Plumes emitted from stacks located near the shoreline fumigate when they intersect this convective boundary layer. In the following section a fumigation model developed by Misra (1980) is described.

Misra (1980) assumed that the dispersion of pollutants within the stable layer and within the thermal internal boundary layer proceeds independently. This is because the turbulent characteristics of each layer are different from the other and they are separated by a fairly well defined surface (i.e the top of the boundary layer). When the plume intersects the thermal internal boundary layer, dispersion into the boundary layer is assumed to occur from an area source located under the surface of the top of the boundary layer. The model assumes vertical and crosswind Gaussian distribution of the plume in the stable layer; and a uniform vertical distribution and Gaussian crosswind distribution of the plume in the internal boundary layer. Then the ground level concentrations are:

$$C(x,y) = \frac{Q}{2\pi H u_m} \int_0^x \frac{1}{\sigma'} \exp \left[-\frac{(H-h)^2}{2\sigma_{z_s}^2} - \frac{y^2}{2\sigma'^2} \right] \frac{d}{dx'} \left[\frac{(H-h)}{\sigma_{z_s}} \right] dx' \quad (1)$$

where: $\sigma'^2 = \sigma_{y_s}^2(x') + \sigma_{y_c}^2(x-x')$ is the net lateral spread

H is the internal boundary layer height

h is the plume height (stack height + plume rise)

u_m is the mean wind speed in the boundary layer

σ_y and σ_z are the standard deviations of the plume in the vertical and crosswind directions.

Q is the emission rate.

x' is the distance downwind from the point on the boundary layer interface where the plume intersects the convective boundary layer.

Note that the subscripts 'c' and 's' refer to convective and stable regimes respectively. For further details on the model see Misra(1980).

Boundary layer height can be obtained from

$$H = A x^{\frac{1}{2}} \quad (2)$$

where A is the parameter which determines the slope of the parabolic profile and x is the distance downwind from the shoreline.

A can be prescribed a priori of climatological data or it can be calculated from

$$A = (u_* / u_m) \left(\frac{2(\theta_L - \theta_w)}{\gamma} \right)^{\frac{1}{2}} \quad (3)$$

where u_* is the friction velocity over land
 θ_L and θ_w are the potential temperatures over land and water respectively,

and γ is the lapse rate over water $\partial\theta_w / \partial z$.

In the stable layer, plume spread is essentially due to self-generated turbulence which is caused by the momentum and/or buoyancy of the plume. The diffusion parameters in this layer are given as follows (Briggs 1975) :

$$\sigma_{z_s} = a_1 (F/u_s)^{1/3} (x/u_s)^{2/3} \text{ for } x/u_s \leq \tau \quad (4)$$

$$= a_2 \quad \text{for } x/u_s \leq \tau$$

$$\text{and } \sigma_{y_s} = a_3 (F/u_s)^{1/3} (x/u_s)^{2/3}$$

Where a_1 , a_2 and a_3 were determined to be 0.5, 0.7 and 1.1 respectively for the Nanticoke generating station plume. For other locations they will be slightly different and can be determined experimentally if required.

F is the initial plume buoyancy flux and

$$\tau = 4.5 \omega^{-1}$$

ω is the Brunt Vaisalla frequency and defines a time after which the plume levels off in the stable layer. The Brunt Vaisalla frequency may be determined from the lapse rate in the stable air, γ .

In the convective layer, results of Lamb(1978) and Willis and Deardorff (1978) are followed. For stacks lying within the mixed layer Lamb (1978) proposed the following :

$$\sigma_{y_c} = 1/3 (w_{*}/u_m)(x-x') \text{ for } (x-x') \leq Hu_m/w_{*} \quad (5)$$

$$= 1/3 (w_{*}/u_m)H^{1/3} (x-x')^{2/3} \text{ for } (x-x') > Hu_m/w_{*}$$

w_* is the convective velocity scale and is defined by

$$w_* = (gH_0Q / \bar{T})^{1/3} \quad (6)$$

with $Q_0 = H_0/\rho c_p$ where H_0 is the surface heat flux, c_p is specific heat at constant pressure, g is the acceleration due to gravity, $\bar{T}$ is the average mixed layer temperature, ρ is the density of air.

Note: For the derivation of u_* , w_* and H_0 refer to Chapter 5 in the yellow bound report entitled "Air Quality Models Suitable for Regulatory Applications."

The shoreline fumigation model has been verified with data from the Nanticoke field study of May 28 to June 14, 1979 (Misra, 1980; Misra and Onlock, 1982). The model predictions agree well with the observed values. The parameters defining the state of the on-shore flow were the primary factors affecting the results of the model. The parameter which determines the height of the boundary layer, and hence, the location and size of the fumigation zone, was found to be important. Therefore care should be exercised in specifying its value. The evaluation of plume rise was also found to be critical.

Recommended Steps for Application of the Shoreline Model

1. For on-shore flows during convective conditions, compute boundary layer heights near the shoreline with equation (1) for a range of values of A between 1.5 and 5, with increments of 0.5.
2. If the boundary layer height at the stack is less than or equal to the stack height use equations (1), (2), (4), (5) and (6) of this report to compute downwind concentrations.
3. If the boundary layer heights at the stack as computed above are greater than the stack height, compute concentration using the

equations given in Chapter V, Air Pollution General Regulation Workshop November 1985, "Air Quality Models Suitable For Regulatory Applications". Do not include plume penetration.

For all other situations use the modelling approach described in the above report.

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